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The American University in Cairo

School of Sciences and Engineering

The Impact of the Death Criterion on the WSN  
Lifetime using EM Pollution Monitoring Algorithm

A Thesis Submitted to

Electronics and Communication Engineering Department

in partial fulfillment of the requirements for  
the degree of Master of Science

by Sara Galal Khalaf Nouh

under the supervision of Prof. Hassanein H. Amer  
May 2017

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## Abstract

Wireless sensor networks (WSNs) are one of the most advanced means that are used for monitoring and reporting. The fact that they consist of small, low cost sensor nodes that are continuously used in a variety of applications has made them become a very attractive field in research. One of the main applications of interest in this research is monitoring the electromagnetic (EM) pollution caused by the rapid expansion of electronic and wireless devices. Research has proven that radiations that these devices emit have a huge effect on the human's health and therefore are worth monitoring. An advanced algorithm was developed in order to monitor these emissions and its main parameters were randomized to give the algorithm a room of flexibility to suit a variety of monitoring scenarios. Although WSNs are used in numerous critical applications, they still face some challenges. Relying on battery-operated sensors causes the network to be resource constrained and therefore, there is a continuous need for prolonging the network lifetime. In this thesis, different death criteria will be applied and their effect on the network lifetime will be investigated. Moreover the impact of changing the number of sensing cycles per network master will be investigated, since the main aim is to exploit the sensor's energy efficiently. Finally, the selection of network master will be examined, i.e., random vs. planned to evaluate its effect on the previous simulations and more importantly on the network lifetime.

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## List of Abbreviations

<b>ADV</b>	Advertisement Message
<b>CH</b>	Cluster Head
<b>DSSS</b>	Direct Sequence Spread Spectrum
<b>EM Pollution</b>	Electromagnetic Pollution
<b>FDMA</b>	Frequency Division Multiple Access
<b>FM Radio</b>	Frequency Modulation Radio
<b>GPRS</b>	General Packet Radio Service
<b>GSM</b>	Global System for Mobile communications
<b>LEACH</b>	Low-Energy Adaptive Clustering Hierarchy
<b>LEACH-C</b>	Low-Energy Adaptive Clustering Hierarchy - Centralized
<b>MAC Protocol</b>	Medium Access Control Protocol
<b>MTE</b>	Minimum Transmission Energy
<b>NM</b>	Network Master
<b>SOSUS</b>	Sound Surveillance System
<b>TDMA</b>	Time Division Multiple Access
<b>UMTS</b>	Universal Mobile Telecommunications Service
<b>WSN</b>	Wireless Sensor Networks

# Chapter 1

## 1 Introduction

### 1.1 Background

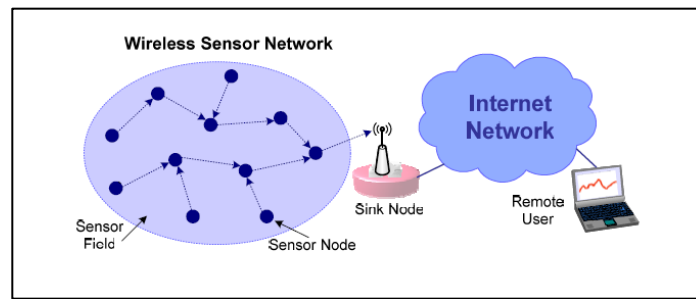
Wireless sensor networks (WSN) have been recently recognized as one of the major prospective technologies due to their wide range of applications and usage in the day-to-day life. Looking back into history it is very likely that like various advance technologies, the WSN has actually originated from the military and industrial applications [Silicon Lab., 2013 and Chaturvedi, 2014]. The first wireless sensor network that was almost similar to the current deployed networks is the Sound Surveillance System (SOSUS). It was first developed in the 1950s by the United States Military to detect and track the Soviet submarines [Silicon Lab., 2013 and Chaturvedi, 2014]. This network relied on underwater acoustic sensors that were distributed in the Atlantic and Pacific Ocean. Despite the fact that this network was built in the 19<sup>th</sup> century, it is still active, however it is currently monitoring only undersea wildlife and volcanic activities.

Nowadays the WSNs are utilized as monitoring tools not only in military and security applications but also in various other functions, such as civil applications that are related to human's health monitoring [Baker, 2007], home automation and alarm system, environmental and industrial monitoring and many others [Sohraby, 2007; Fan, 2010; Mikhaylov, 2012 and Aldeer, 2013]. Therefore, the WSN is currently a very active research area that is trying to solve many challenges that involve energy consumption, routing protocols, deployments algorithms, robustness, efficiency and so on [C-Mancilla, 2016]. However, the main challenge in all those application is keeping the network functional and alive.

### 1.2 WSN Definition

A WSN is composed of a group of sensor nodes that are physically distributed either randomly or using a certain deployment structure in a geographical area that is also called the sensing field [Trad, 2014]. A sensor node or also called a “mote” is a very

small, cheap and intelligent device that can perform several tasks, such as sensing, processing and wirelessly communicating with other sensors [Aldeer, 2013]. This communication enables them to send their sensed data to another node that is acting as a central processing unit and is called “gateway”, “sink” or “base station” [Aldeer, 2013]. The sink is a high energy computing system that is responsible for network organization, receiving information from the distributed sensors and sending it to other external devices as illustrated in Figure 1-1 using various network technologies such as Wifi, Ethernet, satellite, Global System for Mobile communications (GSM) and General Packet Radio Service (GPRS) [Aldeer, 2013]. A single sensor node consists of several hardware components, which are an embedded processor, a radio transceiver, memory chip, power source and a single or multiple sensors [Wang, 2010].



**Figure 1-1 A Wireless Sensor Network Architecture [Trad, 2014]**

### **1.3 Thesis Problem Statement**

The fact that WSN owns this versatile characteristic makes it able to suit a wide variety of applications as mentioned before. Additionally, the sensors could be deployed in inaccessible locations and are also able to withstand harsh environmental conditions, which justifies why WSN was initially used in military applications. Recently, the applications that the WSN could cover are classified into two categories. The first one covers the military and security applications, while the second one covers all civil applications [Wang, 2010 and Aldeer, 2013], which includes healthcare, industrial and environmental functions. Although WSN covers this wide range of applications, it is still subject to a variety of challenges and constraints. Some of these challenges are reliability,

node size, mobility, privacy and security and most importantly power consumption [Nack, 2008 and Fischione, 2014]. Since the sensor nodes are battery operated and are also very small, this limits the lifetime of the node. When the sensor's battery is depleted, it could be either replaced or recharged in case it is relying on solar power. However, in most cases it is more efficient and economical to just discard the whole sensor, due to its insignificant cost, once its energy is depleted and replace it by another one [Fischione, 2014]. Therefore, most of the current WSN research focuses on how to efficiently consume the sensor's energy in order to prolong the network's lifetime as much as possible. In this thesis, this WSN challenge is going to be tackled, by examining several network parameters and introducing new lifetime definitions. Additionally, the Electromagnetic (EM) pollution is chosen to be the application for the proposed algorithm. EM pollution covers two kinds of pollution: natural pollution that contains volcanic eruptions, lightning, and earthquakes [Guo, 2010] and the manmade pollution. It is the excessive EM radiations that are produced from all the electronic devices and wireless communication surrounded by the people such as Wi-Fi, GSM, Universal Mobile Telecommunications Service (UMTS), Frequency Modulation (FM) Radio, TV, power systems, transmission powers, mobile phones, mobile communications systems, radar and satellite ground stations [Djuric, 2011] affecting the human's health directly [Viani, 2011] depending on the frequency of the sources. Sources that produce high frequency have a thermal effect on human beings. This causes a rise in temperature of human tissue that can lead to visual problems, internal burn on the heart vascular system, insomnia, leucopenia, reduction of sexual function, sudden abortion and fetal malformation [Zhang, 2003; Zhou, 2005]. On the other hand sources that produce low frequencies that range from 50Hz to 60Hz [Crede, 1995] cause a non-thermal effect, which can lead to cells mutation and the development of cancer. According to the World Health Organization (WHO) the international Agency for Research on Cancer (IARC), has reviewed the carcinogenic potential of radiofrequency fields caused by the use of mobile phones [WHO, 2014]. Moreover, the Institute of Electrical and Electronics Engineers (IEEE) has advised that in order to limit harmful effects for human beings exposed to electromagnetic fields, the frequency range has to be from 3 kHz to 300 GHz

[IEEE, 2006]. Therefore, due to its hazardous influence, it is worth monitoring and reporting in order to keep the emission level within the acceptable, safe range.

## **1.4 Thesis Contribution**

The contribution of this thesis is mainly developing a generalized algorithm that is based on the system developed in [AbouElSeoud, 2010]. It also analyzes the different parameters used in this system and introduces random variables instead, using different random distributions. Additionally, new network lifetime definitions will also be introduced and their effect on lifetime will be examined. Finally, different number cycles per NM in addition to random NM selection will be studied.

## **1.5 Thesis Organization**

This thesis is organized as follows. Chapter 2 focuses on the literature review, which describes the Low-Energy Adaptive Clustering Hierarchy (LEACH) and its improvement Low-Energy Adaptive Clustering Hierarchy - Centralized (LEACH-C), which is an energy efficient routing protocol. Moreover, section 2.2 demonstrates a lifetime optimization algorithm, which has enhanced the drawbacks in LEACH-C. Section 2.3 includes the previous work and presents the architecture of the EM monitoring algorithm on which all the research is based. Chapter 3 highlights the change of the main parameters in the event-by-event algorithm to random variables and studies their effect on lifetime. It also examines the use of different random distributions for those random variables. Chapter 4 focuses on examining the network lifetime definition. It presents different death criteria and evaluates them according to their energy efficiency using different number of cycles per network master and also a different network master selection approach. Chapter 5 contains the conclusion and chapter 6 introduces the future work based on this thesis research.

# Chapter 2

## 2 Literature Review

### 2.1 Energy Efficient Protocols: LEACH and LEACH-C

#### 2.1.1 Low-Energy Adaptive Clustering Hierarchy (LEACH)

LEACH is a typical hierarchical clustering routing protocol that is proposed by Heinzelman [Heinzelman, 2000 and Dhawan, 2014]. It is one of the most popular routing protocols, since it introduced the most energy efficient routing algorithm that aim is to reduce the network power consumption and at the same time increase the network lifetime [Singh, 2010; Renugadevi, 2012 and Braman, 2014].

#### 2.1.2 LEACH Architecture

First of all, there are two main assumptions considered in the LEACH technique, which are:

- The base station is fixed and located far from the sensors.
- All nodes in the network are homogeneous and energy- constrained.

LEACH is based on the clustering technique, where nodes organize themselves into clusters and each cluster will have a cluster-head (CH). At the beginning, the adaptive clustering protocol uses randomization in order to distribute the energy evenly among all the sensors in the network. Additionally, nodes are selected as cluster head in a circular and random manner in order to optimize the network energy efficiently [Dhawan, 2014]. If the chosen cluster head was kept to be the same during the network lifetime as in many conventional clustering algorithms, then this cluster head will quickly deplete its energy and also the energy of the nodes belonging to that cluster head, causing the whole network lifetime to decrease [Heinzelman, 2000]. Therefore, LEACH randomly rotates the high-energy cluster head position among the various sensors in order not to deplete the battery of a single sensor at a time. The normal nodes that exist within one cluster are called the cluster nodes. Their role is to sense the required data and send it directly to the



cluster head. Afterwards, the cluster head received the sensed data from all the sensors within that cluster, aggregates it in order to remove any redundant data and then applies the fusion process and sends the data to the sink or base station. The data fusion process is another meaning for data aggregation, where unreliable data measurements are combined in order to produce a more accurate signal and reduce uncorrelated noise. This helps avoid information overload. Hence, LEACH prolongs the network lifetime by reducing the number of communication messages using data aggregation and fusion and accordingly consuming less energy within the network.

In the development of LEACH there are some assumptions that are made for the sensors and also the network model:

- All nodes can transmit with enough power in order to reach the sink if needed
- The nodes are able to vary the transmit power using power control
- Each node is able to support different MAC protocols
- Each node can perform signal power functions using its computational power.
- The nodes always have data to send to the end user
- Nodes located close to each other always have correlated data

### 2.1.3 LEACH Algorithm

The LEACH operation is divided into rounds. Each round starts with a set-up phase, this is when the clusters are organized. The second phase is the steady phase. In this phase, the data are being transferred from the nodes to the cluster head and then to the sink as shown in Figure 2.1. It could be obtained that the steady state is much longer than the set-up phase, in order to minimize the overhead as much as possible.



**Figure 2-1 Several Rounds, where adaptive clusters are formed during the Set-up time and data is transferred during the Steady-state time [Heinzelman, 2002].**

The cluster head selection and the distributed cluster formation algorithm as well as the steady- state operation will be discussed in the following subsections.

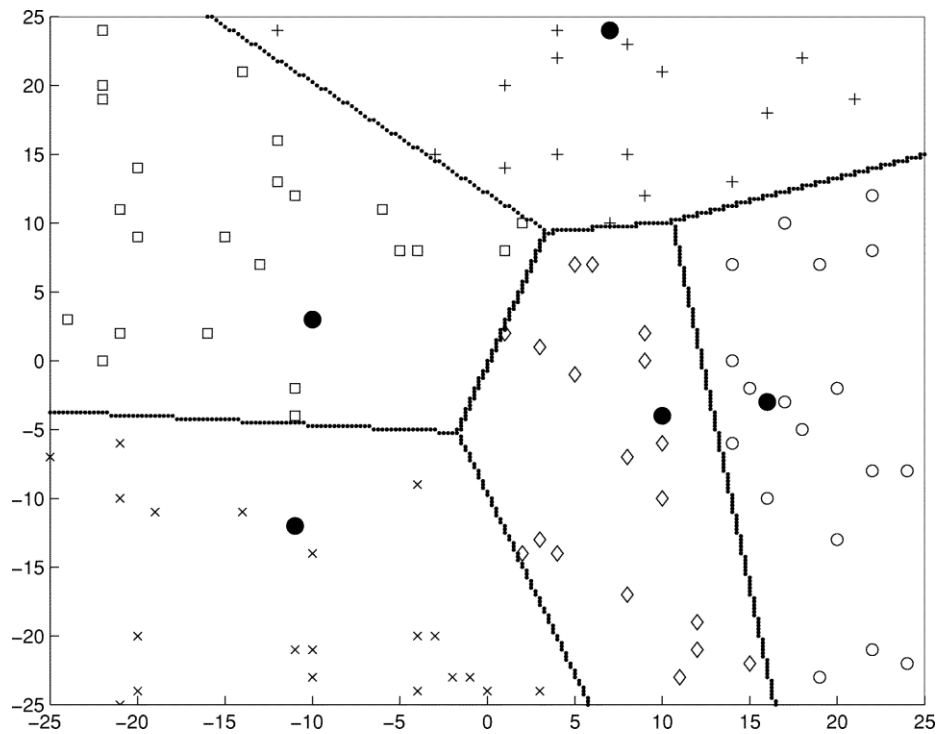
#### 2.2.3.1 Cluster Head Selection

As mentioned before it is assumed in the LEACH algorithm from the beginning that all nodes should possess the same initial energy. There reason for that is to distribute the energy load evenly among all sensors, so that no node depletes its energy faster than the other ones. The goal of this algorithm is to have a specific number of clusters  $k$  in each round  $r$ . Since being a cluster head is very energy consuming than just being a non-cluster node, this demands that each sensor should take its turn in acting as a cluster head. Hence, this algorithm assures that all nodes act as cluster heads for the same number of times, which requires that every sensor on average should act as a cluster head once every  $N/k$  rounds. The variable  $N$  here is the number of nodes, while  $k$  represents the number of clusters. The function  $C_i(t)$  indicates whether each node has acted as a cluster head or not using a 0 and 1 value. The 0 value indicates that the node has acted as a cluster head and if the value is 1 it indicates otherwise. Using a probability function calculated in [Heinzelman, 2002] the cluster heads for the next rounds are chosen. Therefore, when there are nodes that did not act as cluster heads during the recent round and still have excess of energy compared to the rest of the nodes, they will be allowed to act as cluster heads during the next round. In order to compute these probabilities, it is assumed that each node knows the parameters  $k$  and  $N$  from the start. Hence, this algorithm is not very suitable for dynamic networks. The reason for that is that the number clusters  $k$  is a function of the number of nodes  $N$  that is distributed in an  $M \times M$  area. Hence, the nodes will determine  $N$  assuming there is predefined parameter  $M$ . In order to indicate the value of  $N$ , each node should send the same message to its neighbors using a predefined number of hops and then each node should count the number of messages it receives. Accordingly the value of  $N$  will be estimated and the number of cluster  $k$  can be calculated. This allows the LEACH to adapt to different networks, however at the cost of the increased overhead.

### 2.2.3.2 Set-Up Phase

During the set-up phase, the cluster formation takes place. At the beginning, the probabilities are being calculated and the nodes with the highest probability announce to the rest of the nodes that they for act as cluster heads during that round. The announcement happens by sending an advertisement message (ADV) that contains the node's ID and a header affirming the identity of the message. Afterwards each node chooses the closest cluster head according to the signal strength and clusters start to get formed. This will ensure that energy is consumed properly within the network. In the case of ties, random cluster heads are chosen.

After each node has identified its cluster head node, it should also send a join-request to that cluster head. The message includes the node's ID as well as the cluster head's ID. When this message is sent, the cluster head then sends to each node within that cluster a TDMA schedule to avoid data collision. The following Figure 2-2 shows an example of a network divided into several clusters, where black node indicates the cluster head of each cluster [Heinzelman, 2002].



**Figure 2-2 An example of a Clustered Network [Heinzelman, 2002]**

### 2.2.3.3 Steady-State Phase

The steady-state phase includes the data transmission from the nodes to the cluster head and from the cluster head to the base station. It is divided in frames, where the nodes should send their sensed data to the cluster head maximum once per frame and also during its allowed transmission slot. This allocated time slot is constant for all the nodes and depends on the number of nodes within the cluster. It is assumed that all nodes are synchronized and start at the same time during the set-up phase. This could be achieved by the sink that will be responsible for sending out synchronization pulses to the nodes. As previously mentioned, the cluster nodes use power control in order to manage the amount of energy they transmit. Moreover, in order to reduce the energy dissipation more, the radio of the each node is turned off until it is its turn to transmit data during its allocated time slot. Hence, using a TDMA schedule allows the bandwidth to be used efficiently and achieves low latency as well. On the other hand, the cluster head is assumed to be awake all the time to receive the data from the cluster nodes. Once it has received all the data it starts aggregating them and sending them to the sink. This might require a high-energy transmission, in case the sink is located far away.

In some cases, inter-cluster interference exists and in order to reduce that each cluster should communicate using a direct-sequence spread spectrum (DSSS). Each cluster will own its unique code, where the nodes within this cluster should use this code while sending their data to the current cluster head. On the other side, the cluster head should filter the received data using this spreading code. Transmitter-based code assignment is the method known to make all the sensor nodes within one cluster share the same code [Hu, 1993]. The first node that announces itself as a cluster is assigned the first code using a predefined list. Then the 2nd cluster head takes the second code and so on. The advantage of DSSS is that it can cope with changing networks unlike Frequency Division Multiple Access (FDMA). However, it needs exact timing synchronization, which requires extra communication between node members and cluster head [Heinzelman, 2002].

#### 2.2.3.4 Optimum number of clusters

The previous assumptions were simulated using 100 nodes that are randomly deployed in a  $100 \times 100 \text{ m}^2$  area. Analyzing the results, it showed that the optimum number of clusters lies between 3-5 clusters within that specific area. Hence, the optimal number of cluster heads was calculated to be around 5% of the total number of node. This means that if the network consists of only one cluster, then some sensors will be very far from the cluster head causing the energy of those sensors to deplete very fast. Also, if there are more than five clusters per network then the data aggregation will be very minimal, causing much more overhead. Figure 2-3 illustrates the average energy dissipated per round, which is a function of the number of clusters. It also confirms the results previously obtained, namely that the optimum number of clusters per network should be between 3-5 clusters [Heinzelman, 2002].

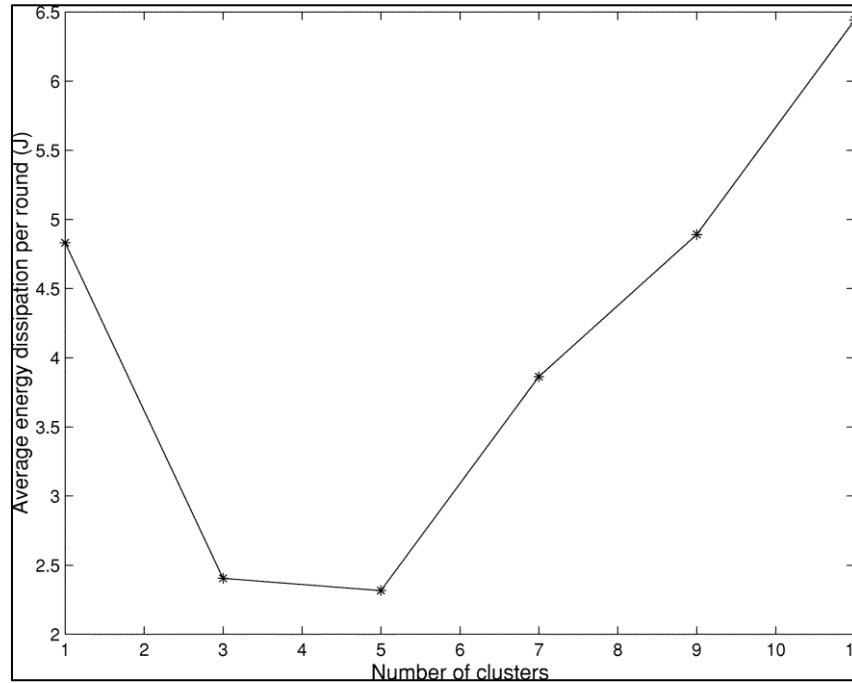


Figure 2-3 Optimum number of Cycles per round in LEACH [Heinzelman, 2002]

#### 2.1.4 Low-Energy Adaptive Clustering Hierarchy – Centralized (LEACH-C)

The previous section showed that LEACH uses a distributed cluster formation algorithm, which has many benefits. However, it does not guarantee a specific number of

cluster heads or their location. It is very common that in one of the rounds the location of the selected cluster heads will not be optimum, still this will not have a great impact on the network performance, since the clusters are adaptive. Nevertheless, applying LEACH- Centralized (LEACH-C) might produce better clusters, since the cluster heads will be dispersed all over the network. LEACH-C uses a centralized clustering algorithm while maintaining the same steady-state phase as LEACH.

What distinguishes the LEACH-C from LEACH is the set-up phase. In the LEACH-C, each node should send its location and energy level to the sink. The sink needs to assure that the energy load is evenly distributed among all sensors. Hence, it calculates the average node energy and the nodes, which energy level is below that average, will not be able to act as cluster heads for that round. Using a simulated annealing algorithm [Murata, 1994], the optimum number of clusters is calculated and accordingly cluster heads are chosen from the sensors whose energy level is above the average energy. This algorithm aims to minimize the sum of squared distances between cluster nodes and the nearest cluster head.

When the cluster heads and their associated sensor nodes are determined, the sink starts to send the cluster head's ID to the node. If this ID is identical with the node's ID, then this means that this node is the cluster head. Moreover, the cluster nodes identify their transmission slot and sleep until it is active so that they start sending out their data. This implies that the steady-state phase of LEACH and LEACH-C is almost the same [Heinzelman, 2002].

#### **2.1.5 Comparing LEACH and LEACH-C with other schemes**

It is very important to compare LEACH's performance however in contrast with other protocols. Hence, a fair comparison will be demonstrated in the next figures between LEACH, LEACH-C, minimum transmission energy (MTE) and static clustering with respect to amount of data transfer, energy dissipation, latency and system lifetime.

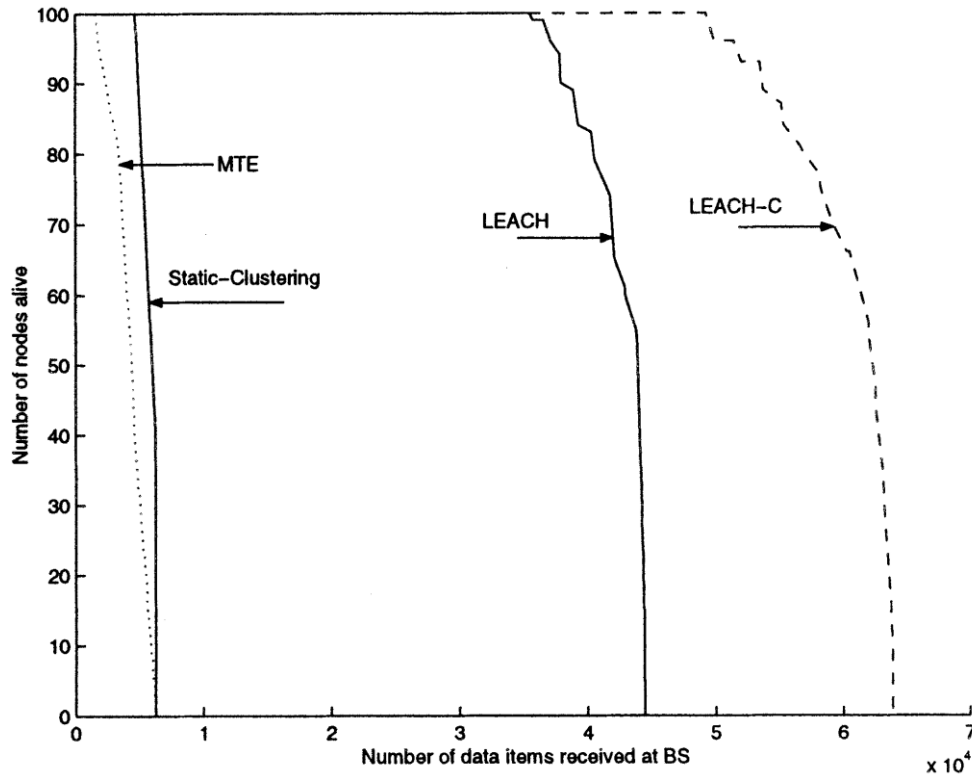
The MTE routing protocol relies on the fact that each node in the network is aware of each sensor's location. Hence, each node determines the next-hop neighbor, which is closest to the sink, during its own start-up routine. The data are then transferred using the next-hop neighbor from one sensor to the other until it reaches to the sink. On the other

hand, the static clustering technique is based on having the same organized clusters and the same selected cluster heads during the whole period of operation, until the cluster heads deplete their energy. Comparing all four schemes together LEACH, LEAVH-C, MTE and static clustering, LEACH has achieved reduction in energy by a factor of 4-8 compared to the MTE routing protocol [Botros, 2009]. Also, LEACH and LEACH-C achieve more energy and latency efficiency, since they are able to transfer the most data per unit energy. On the other hand, the MTE protocol does not perform data aggregation in order to reduce the amount of data transmitted to the sink.

Comparing LEACH with LEACH-C, LEACH-C achieves a better performance than LEACH by transmitting 40% more data per unit energy. The reason for this is that the sink in LEACH-C is aware of the location and energy level of the nodes, hence is able to produce better clusters using the centralized clustering algorithm that consume the energy efficiently while transmitting the data.

The next Figure 2-4 shows the different schemes together and for each one, the total number of nodes that are alive with respect to the data items received by the sink. It is clear that LEACH is more effective than the MTE routing protocol and can transmit 10 times the data items sent by MTE using the same number of nodes. The reasons that MTE nodes deplete their energy very fast are due to:

- 1) Lack of data aggregation
- 2) Collision



**Figure 2-4 Number of Nodes alive per amount of data sent to the Sink [Heinzelman, 2002]**

The MTE protocol does not rely on a centralized control time of the transmission and receiving of data causing collisions and loss of data that will consume much more energy to send a correct message. Additionally this technique requires almost 6 hops in order for the data to reach to the sink, while in LEACH it only requires one hop, which is from the cluster head to the sink.

On the other hand, the static clustering shows a very bad performance in Figure 2-4. This is due to exploiting the energy of the cluster heads during the network life cycle causing these sensors to die fast. Hence, it is very important to rotate the selection of the cluster head position, in order to achieve higher lifetime as shown in the examples of LEACH and LEACH-C.

## 2.2 Lifetime Optimization for Clustered WSN

Although LEACH-C has a achieved a higher performance than LEACH by



equally distributing the energy between the sensors and positioning the cluster heads at the center of the clusters, while maintaining the same steady-state phase protocol [Nam, 2008], it still has some drawbacks. One of these drawbacks is the energy overhead consumed in the cluster heads selection. Moreover, in case of depleted sensors, LEACH-C loses its full coverage of the network, although there are still some sensors in the network that still possess residual energy. Henceforth, a technique was proposed in [Botros, 2009] in order to overcome these drawbacks by finding the optimum number of cycles per Network Master (NM), which was referred to as CH by LEACH [Heinzelman, 2000]. In [Botros, 2009], the sink is responsible for calculating the number cycles for each sensor that will be able to act as NM. Moreover, based on preset criteria, it chooses which sensor will be NM for a specific number round. If each sensor acts as NM only once, then this algorithm will achieve a much higher lifetime than LEACH-C, since the sensor's residual energy will be consumed efficiently.

In this algorithm, the network consists of one cluster, where the sensors are randomly distributed. This could be applied to some critical applications like explosive detection [Aldeer, 2013], where the sensors are randomly deployed from an aircraft over a specific area. Those deployed sensors are assumed to be homogenous and energy constrained. It is assumed as in LEACH that sensor locations are known to the sink as well as to all the sensors. Every round, a sensor is selected by the sink to act as a network master, collects the data from the rest of the sensors, aggregates it, removes redundancy and sends it to the sink. The sink location is a bit far from the network, as in some cases it is hard to place it close to the sensors. However, if that would be the case and the sink was placed closer to the sensors, it would have consumed less energy, since the distance between the sensors and the sink would have been much less [Botros, 2009].

### **2.2.1 NM Selection Criteria**

In this algorithm, the sink chooses the sensor with sufficient energy to act as NM for a specific number of cycles “C”, which is also known as one round. During these cycles, all the rest of the sensors send their sensed data to the NM, which aggregates it and compresses it and then sends it to the sink. The next round starts when the current

NM reaches its threshold and another sensor is selected to act as an NM. There are some energy criteria, which the sink has to evaluate first in to be able to choose the NM for each round; those are:

- 1) “ $En_{Th}$ ” is the energy required for a sensor to send its sensed data to the farthest NM during one complete round.
- 2) “ $En_{ThNM}$ ” is the energy needed for the NM to gather the data from all the sensors, aggregates them and sends the compressed data to the sink for one complete round.

Accordingly, if the sensor achieves the first criteria then it will be able to act as a sensor node and if it additionally achieves the second criteria then it will be able to act as a network master. According to the lifetime definition stated in [Mahfoudh, 2008], the network lifetime is defined by the death of the first node due to battery outage. This means that if one of the sensors its remaining energy is below the  $En_{Th}$  then this sensor is considered dead and accordingly the whole network.

Henceforth the sensors are classified into three classes according to their energies:

- 1) If ( $En_{Sensor} > En_{ThNM}$ ) then those sensors are active sensors that have enough energy to act as NMs.
- 2) If ( $En_{Th} < En_{Sensor} < En_{ThNM}$ ) then those sensors are active sensors that have enough energy to send and receive data, but cannot act as NMs.
- 3) If ( $En_{Sensor} < En_{Th}$ ) then those sensors are inactive.

Since, during each round the sink has to announce the new NM, part of the sensors' energy is wasted in the overhead caused by the reception of these announcements. Hence, there will always be a tradeoff between number of cycles per NM and the energy threshold required for the sensor to act as NM. This was solved by [Botros, 2009] by calculating the optimum number of cycles for the NM for each round.

### 2.2.2 Network Parameters

The same parameters that were used in LEACH, LEACH-C [Heinzelman, 2002] and other publications such as [Wang, 2007; Nam, 2008 and Yeo, 2003] are also used in this algorithm. It relies on a  $100 \times 100 \text{m}^2$  network, where 100 sensors are randomly distributed. The rest of the parameters are the same as [Heinzelman, 2002] and are listed in the following table. The only difference would be the newly introduced energy overhead consumed by the sensors during each round when receiving the announcement of the current NM. It is calculated as 25% of the data packet size [Botros, 2009].

**Table 2-1 Network Parameters of the Lifetime Optimization Algorithm [Botros, 2009]**

Parameter	Symbol	Value	
Network Size	M X M	100 m X 100 m	
Number of Sensors	N	100	Sensors
Transmitter / Receiver Electronics	$E_{elec}$	50	nJ/bit
TX. Amplifier for short distance	$E_{amp-short}$	10	pJ/bit/ $\text{m}^2$
TX. Amplifier for long distance	$E_{amp-long}$	0.0013	pJ/bit/ $\text{m}^4$
Pass Loss Factor for short distance		2	
Pass Loss Factor for long distance		4	
Aggregation Energy	$E_{agg}$	50	nJ/bit/Signal
Data Packet Size		500	Bytes
Overhead Packet Size		125	Bytes

### 2.2.3 Calculating the Optimum number of Cycles

Using the above parameters, the optimum number of cycles “C” was calculated using MatLab [MATLAB]. Different number of cycles was simulated against the network lifetime, where during each “C” the sensor acting as NM remains the same for

one complete round. The next Figure 2-5 illustrates that the highest lifetime value 3702 cycles is achieved when the number of cycles per round using a single NM is  $C=3$ .

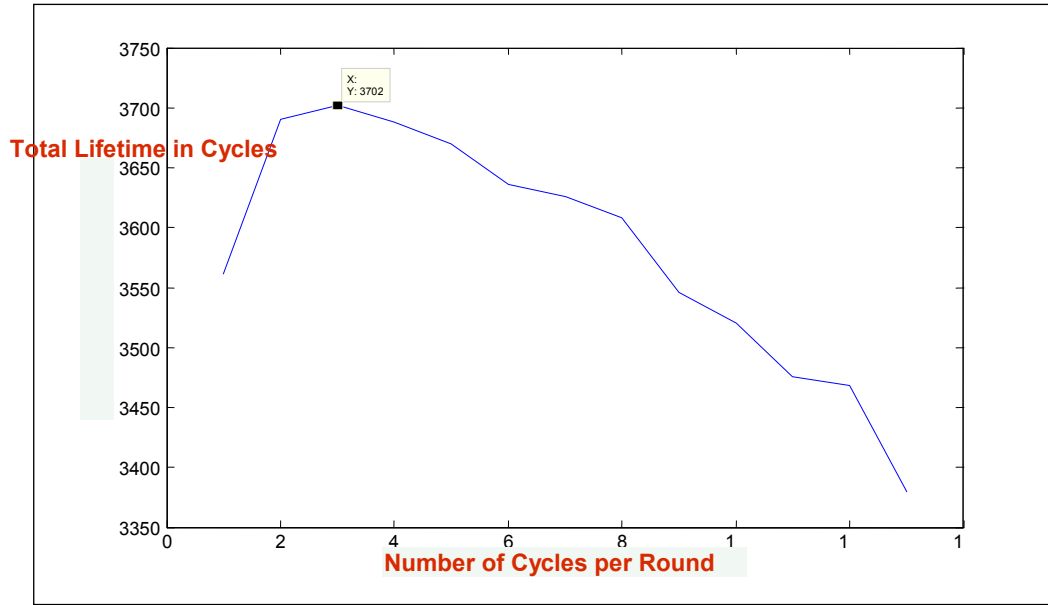


Figure 2-5 Optimum number of Cycles "C" per Network Lifetime [Botros, 2009]

#### 2.2.4 Comparing the results to LEACH-C

For fair comparison, LEACH-C was simulated as one cluster as assumed in [Botros, 2009]. The system has achieved a lifetime of 2950 cycles, which is equivalent to  $C=50$  cycles per round. Comparing this to the algorithm developed by [Botros, 2009], it shows that it has achieved a much higher lifetime value, while using  $C=3$  cycles per round. Additionally, in the new algorithm, all active sensors remain capable of acting as NMs during the whole lifetime of the network, while in LEACH-C the sensors could act as NMs for only one round.

#### 2.2.5 An improved Algorithm to calculate " $C_i$ "

One of the drawbacks of the previous simulations is that the network lifetime is dependent on the death of the first node, while there is still some residual energy in the network that was not used. Another drawback is that the sensor is selected to act as NM several times for very small rounds. In each round, there is an energy overhead consumed in announcing the current NM and in receiving this announcement by the sensors. Hence,

in order to overcome these drawbacks, an improved algorithm was developed by [Botros, 2009] that assigns from the beginning to each sensor the role of acting as NM only once. However, the number of cycles for each NM will not be constant like the previous example, but will depend on each sensor's energy. This means that every sensor will act as an NM for a different number of cycles " $C_i$ ", in order to maximize the utilization of the sensor's energy. This will lead to decreasing the number of NM announcements and the energy overhead. Accordingly, the number of sensors that will act as NM will increase as well as the network's lifetime. The next Figure 2-7 shows after the simulation the number of cycles " $C_i$ " associated to each sensor while acting as NM. It can be obtained that the number " $C_i$ "s varies between 16 and 46 cycles per round. The total lifetime of this simulation is 3900 cycles, which is higher than the previous fixed " $C$ " cycles per round that resulted in 3702 cycles. Moreover, the order of NMs in this example does not affect the performance and hence no need for the NM selection.

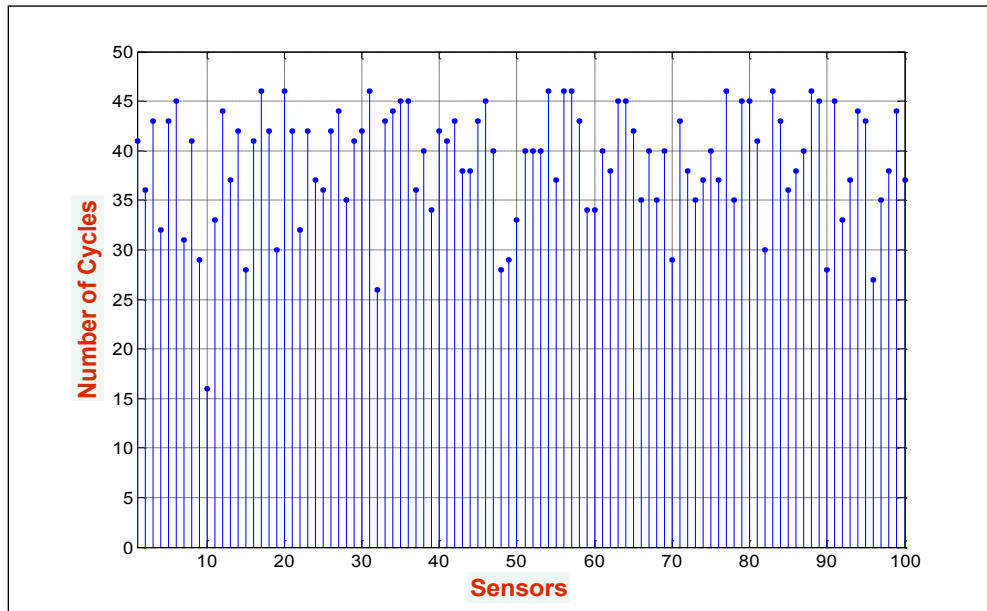


Figure 2-6 Number of Cycles " $C_i$ " for each sensor acting as NM [Botros, 2009]

### 2.2.6 Comparing the improved Algorithm to previous examples

As mentioned before the improved algorithm resulted in network lifetime of 3900 cycles, which is around 5% higher than using fixed number of cycles " $C$ " per round that

resulted in 3702 cycles. Comparing this result also to LEACH-C, it shows that the improved algorithm has prolonged the network lifetime by 32%. The reason for that is the reduced energy overhead since the number of cycles is calculated at the beginning at the sink and no need to select the NM for each round since the order of NMs does not affect the performance. Moreover, there is no energy consumed by announcing the NMs in each round and receiving this announcement by each sensor. The next Figure 2-8 demonstrates a comparison between LEACH-C, the technique used in the previous section using the fixed “C” cycles and last presented the improved algorithm. It shows that the lifetime of the improved technique reaches  $C=3900$  cycles.

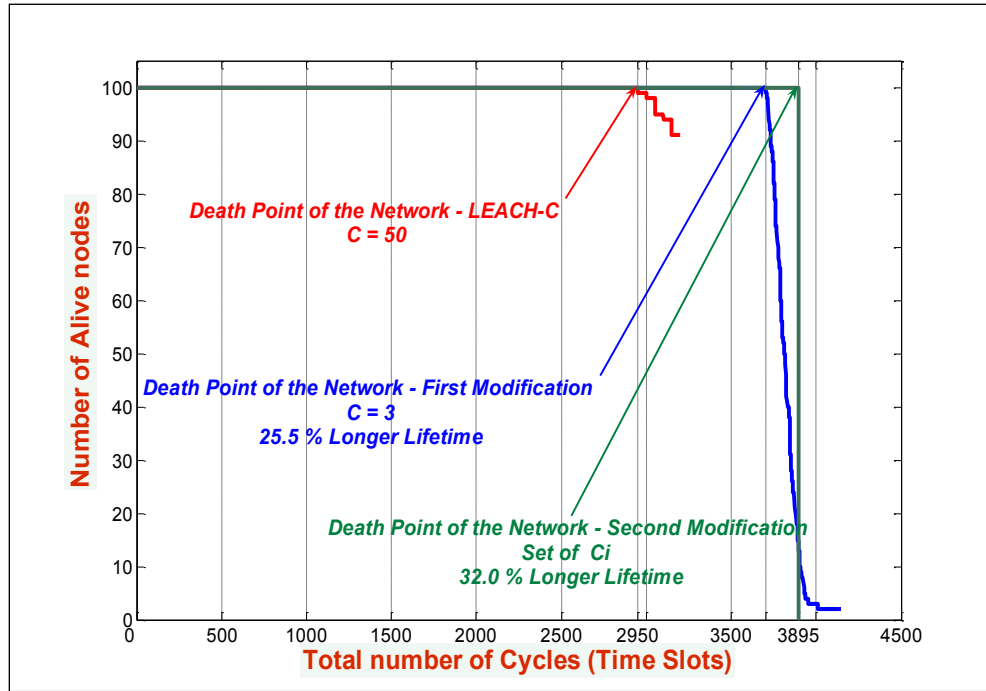


Figure 2-7 Number of alive Nodes vs. Network lifetime in Cycles [Botros, 2009]

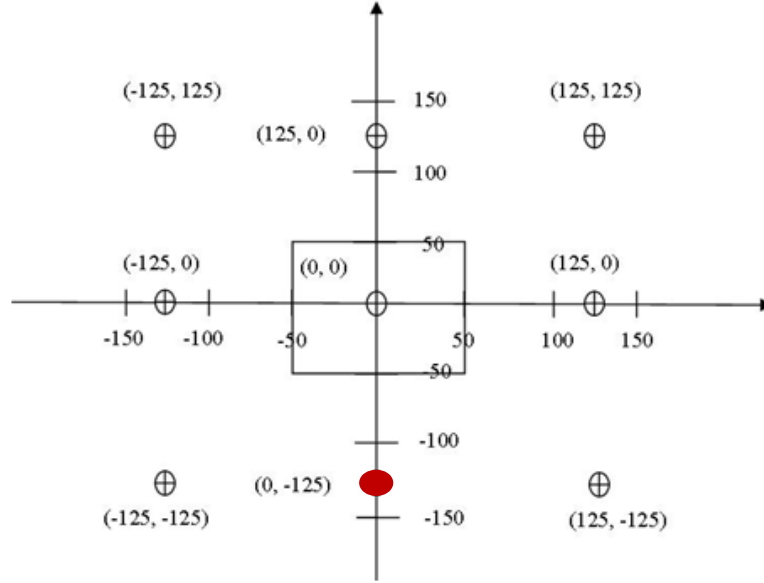
### 2.3 Event-by-Event Algorithm

This section focuses on developing a real time application that could monitor the power violation based on the algorithms described in the pervious sections. As mentioned before, electromagnetic pollution could be very harmful to human’s health if it exceeds a certain threshold; therefore, continuously detecting the violating power

levels is very important. The event-by-event algorithm was designed to suit the special conditions of EM pollution and is event driven, therefore using the Lifetime optimization algorithm in that case was not possible. This developed system does not rely on solving  $N$  equations in  $N$  unknowns like in the Lifetime optimization algorithm, yet uses another technique that is able to detect violations occurring at different times. It goes over the sensors in ascending order, where each sensor acts as NM for “ $C_i$ ” cycles that are not known from them beginning till it reaches a specific threshold and then starts acting as an active node [AbouElSeoud, 2010]. When the active node depletes its energy by reaching a certain threshold, it is considered dead and accordingly the whole network is considered dead as well.

### **2.3.1 Choosing the Adequate Distribution**

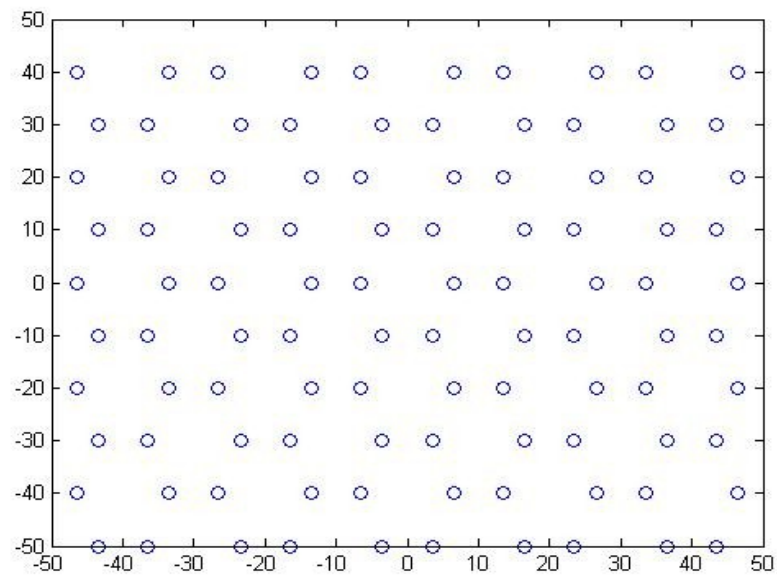
In the previously described algorithms the nodes were randomly distributed in the  $100 \times 100 \text{m}^2$  area, however, there are some applications such as chemical, nuclear and environmental monitoring that do require the sensors to be uniformly distributed. It is very important to choose the adequate distribution for the required application from the start, because sometimes it is very difficult and also expensive to change the sensor's location. Multiple geometric distributions were studied in [Nouh, 2010]. Almost the same parameters that were used in [Botros, 2009] are also used in [Nouh, 2010] and [AbouElSeoud, 2010]. One of the different parameters is the sink location. The sink locations shown in Figure 2-9 were examined on several distributions. It was proven in [Nouh, 2010] that changing the sink position to the (0,0) location achieves highest lifetime, as opposed to the sink location (0, -125j) used in [Botros, 2009] and also to other tested sink locations.



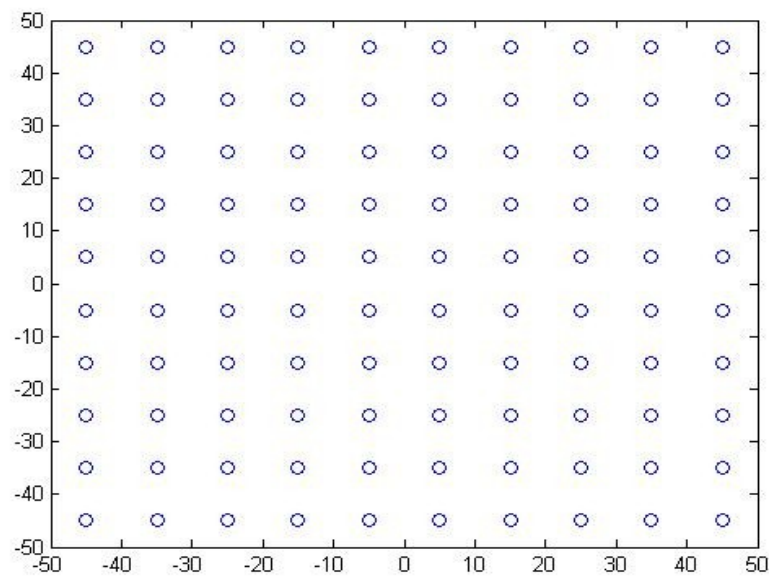
**Figure 2-8 Different Sink locations [Nouh, 2010]**

The uniform distribution is considered as part of the geometric distributions. Three uniform distributions were studied in order to obtain the network distribution that has the highest lifetime. The first distribution is the hexagonal distribution shown in Figure 2-10. This distribution is usually implemented in the cellular communication network due to its broad and comprehensive coverage. The second distribution is the homogenous distribution presented in Figure 2-11, where a sensor is placed in every meter square of the  $100 \times 100 \text{m}^2$  area. Lastly, the circular distribution is illustrated in Figure 2-12, where the number of sensors increases in a circular form as the circles go away from the center. Comparing the lifetime results of all those distributions while placing the sink at the center of each distribution, it turns out that the homogenous distribution has achieved highest lifetime. It resulted in 3301 cycles, whereas the hexagonal distribution and the circular resulted in 3293 and 2876 cycles respectively. This shows that choosing the homogenous distribution for the EM pollution application will be the most fitting choice.

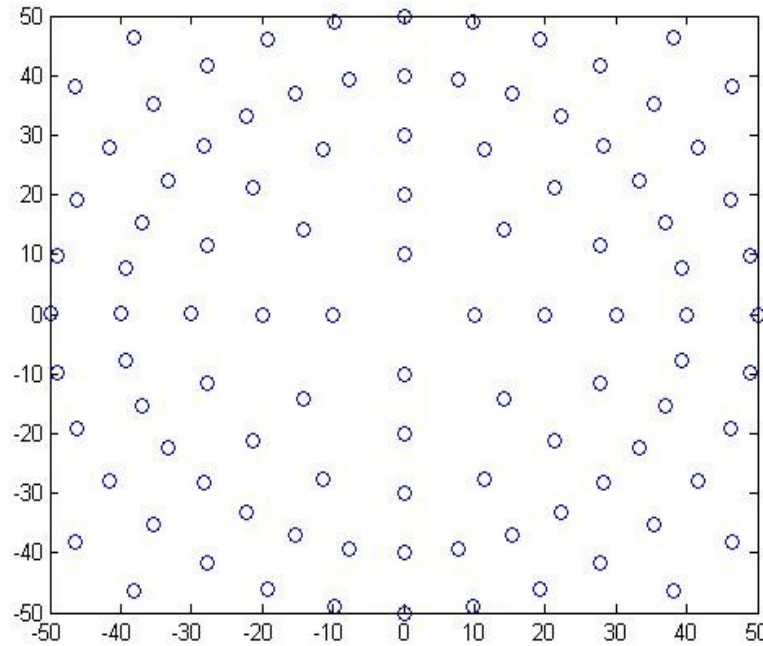




**Figure 2-9 Hexagonal Density Distribution [Nouh, 2010]**



**Figure 2-10 Homogenous/ Uniform Density Distribution [Nouh, 2010]**



**Figure 2-11 Circular Distribution [Nouh, 2010]**

### **2.3.2 Event-by-Event Network Parameters**

As mentioned before the parameters used in the event by event algorithm are very similar to the ones used in the Lifetime Optimization Algorithm in [Botros, 2009]. The first parameter that was used differently than in [Botros, 2009] is the network distribution. The homogenous distribution suits the urban and environmental applications and hence is more applicable for monitoring the EM pollution. The second modified parameter was the sink location, which was proven in [Nouh, 2010] that placing it at the center of the network distribution would yield highest lifetime value. The fourth is choosing a different packet size of data, which is 64 bits instead of 2000 bits. The reason for that is that the messages that will be transmitted to the NM will either include a danger or alive signal, hence are very small messages. It was also proposed in [AbouElSeoud, 2010] that the message sent by the NM is 512 bits. The reason for that is the fact that the NM aggregates the data from the sensors and sends it to the sink; hence it

needs to describe the status of each sensor in 2 bits. The 2 bits produce four combinations that are more than enough to describe the sensor's status. Thus, the needed packet size would be 2 bits x 100 sensors = 200bits. Leaving a room for flexibility in the system it was assumed that this packet size should be 512 bits. Finally, another new parameter called  $E_{sense}$  was added to the rest of the parameters. This parameter indicates the required energy for a sensor to sense the violation or in other words detect the power level of the EM waves. The value of this parameter is calculated as follows:

$$E_{sense} = E_{elec} \times K2 \quad \text{where } K2 = 1 \text{ bit} \quad (2.1)$$

Assuming that 4000 cycles are equivalent to one year, one hour will be equivalent to almost 2 hours and for simplicity it will be assumed that one hour is equivalent to one cycle. The rest of the parameters used in [AbouElSeoud, 2010] are the following:

- Network size:  $100 \times 100 \text{m}^2$
- Number of Sensors (N): 100 Sensors
- Initial Energy: 2 J
- Transmitter/ Receiver Electronics ( $E_{elec}$ ): 50 nJ/bit
- Transmitter Amplifier ( $E_{amp}$ ) : 100 pJ/bit/ $\text{m}^2$
- Path Loss factor (n): 2
- Aggregation Energy ( $E_{agg}$ ): 5 nJ/bit/Signal
- Data packet size sent by active nodes to NM(K): 64 bits
- Data packet size sent by the NM to the sink (K1): 512 bits
- Data packet size equivalent to sensing power levels (K2): 1 bit
- Sink location: (0; 0)
- Distribution: Homogeneous Density

### 2.3.3 Watchdog Technique

In the event-by-event algorithm, there are four frequency polluters being monitored and each frequency polluter is assigned a group of sensors that should send

their sensed data to the current NM if the frequency polluter has violated the acceptable range of transmission. However, there are times when there is no violation coming from the polluters and the active sensor is not sending any messages to the NM. Therefore, it is very important to know if this active sensor is still alive or not, otherwise the whole network will be dead if only one sensor dead. Henceforth, a watchdog technique is applied, where every sensor has to send a packet every predefined period to the current NM indicating whether it is alive or not. This predefined period is assumed here to be every 3 cycles/hours [AbouElSeoud, 2010].

#### 2.3.4 Frequency Polluters

As mentioned in the previous section, this event-by-event algorithm is designed to monitor four frequency polluters. Each one of them is placed on the side of the 100x100m<sup>2</sup> area as indicated in Figure 2-13. It is assumed in [AbouElSeoud, 2010] that each polluter violates during predefined times, which is the last 6 hours of the day every 96 hours. This means that F1 will be violated on the first day from 6pm till 12am, then on the 2<sup>nd</sup> day F2 will violate at the same, then F3 on day 3 and F4 on day 4. Then the process repeats itself every four days. Moreover, the sensors placed in the monitoring area are pre-programmed to monitor one frequency polluter. Hence, there are four groups of 25 sensors; each one of them is associated to a single polluter. However, not all the sensors will sense violation produced by the frequency polluters. The circular curve drawn in Figure 2-13 includes for example the number of sensors from group f1 that will sense the violation. Each semi circle will include the sensors that will sense the violation. The reason for that is that not all sensors will sense the violation especially if they are located far away. Therefore, the closest sensors to the polluters are the ones identified to sense the pollution. These sensors are manually selected and each sensor's number is the identification number in the sensor's array:

```
f1= [2 7 26 34 47 54 55 66 78 83 98]
f2= [1 14 18 22 29 49 65 74 82 89 97]
f3= [4 5 28 36 53 45 56 68 80 81 100]
f4= [3 16 20 24 31 51 67 76 84 91 99]
```

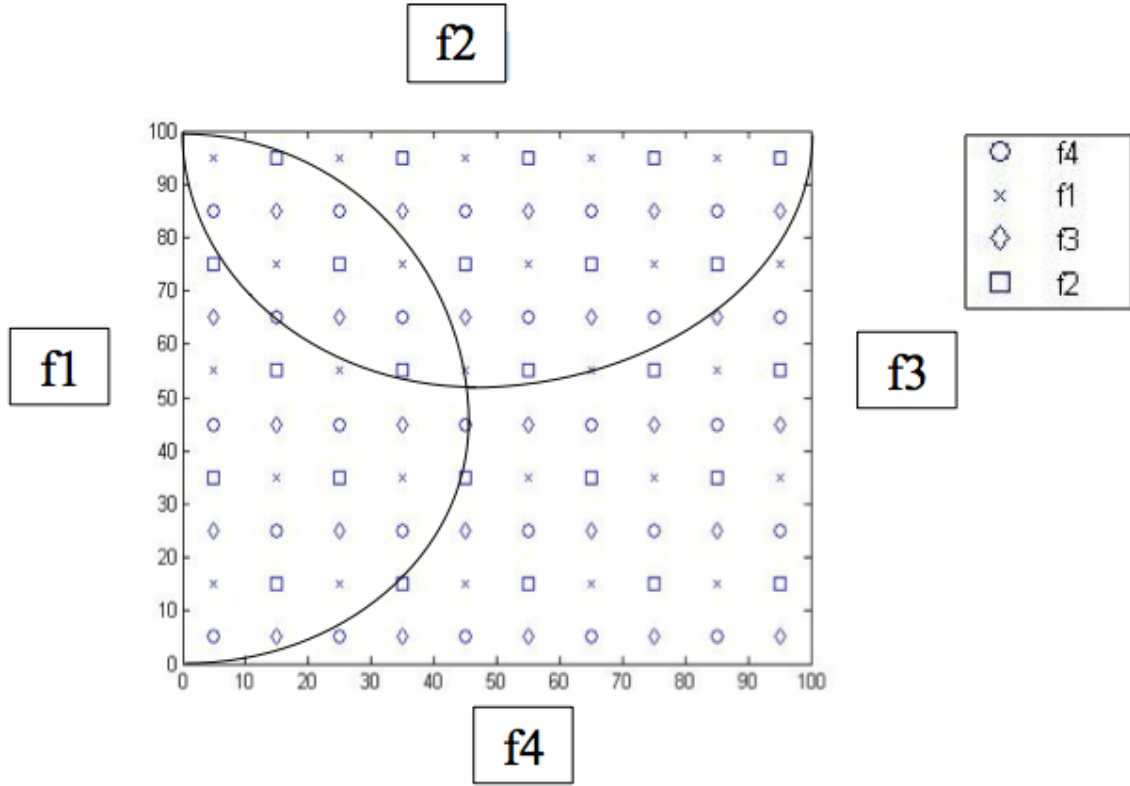


Figure 2-12 Placement of Sensors and their corresponding Frequency Polluters  
[AbouElSeoud, 2010]

### 2.3.5 Sensor Threshold

There are two thresholds associated to each sensor the active node threshold and the NM threshold.

#### 2.3.5.1 The Active node Threshold

The active node threshold is defined as the ability of a sensor to sense and send its sensed data to the current NM. If the sensor's energy goes below that threshold then the sensor is considered dead and accordingly the whole network is dead, since the network lifetime is defined by the death of the 1<sup>st</sup> node. The active node threshold is calculated as follows:

$$E_{active} = E_{sense} + E_{prot} + E_{tx} \quad (2.2)$$

where:

$$E_{sense} = E_{elec} \times K2 \quad (2.3)$$

$$E_{prot} = E_{elec} \times K1 \quad (2.4)$$

$$E_{tx} = E_{amp} \times K1 \times (d_{sink})^n \quad (2.5)$$

where  $d_{sink}$  is the distance between the specific NM and the sink.

#### 2.3.5.2 The NM Threshold

The NM threshold is defined as the energy required for a sensor to act as a network master, receive data from 99 sensors, aggregates it and then sends it to the sink. There are many ways in obtaining the NM threshold, however a good choice would yield a high lifetime value while a poor one would not. Therefore, several methods were investigated in [AbouElSeoud, 2010] to obtain the NM threshold, which will be discussed further in the next section.

#### 2.3.6 NM Threshold

In the Lifetime Optimization algorithm the NM threshold was obtained by calculating the number of cycles “ $C_i$ ” for each sensor before the system starts. However, this could not be the case here since event-by-event algorithm is a real time simulation and its outcome is the number of cycles that is an unknown parameter at the beginning of the process. Hence, several techniques were developed in order to obtain the adequate NM threshold.

##### 2.3.6.1 The Average Technique

The average technique is based on setting one threshold for all sensors, if reached the sensor won't be able to act as NM anymore. The average threshold will be taken from the Lifetime Optimization Algorithm [Botros, 2009] by calculating the total consumed energy of the network and dividing it by the number of sensors. It is calculated as follows:

$$E_{consumed}(i) = C_i \times E_{NM_i} \quad , where i = 1, 2 \dots NM \quad (2.6)$$

$$E_{consumed\_average} = \frac{\sum_{i=1}^{i=NM} E_{thNM}(i)}{no.of NMs} \quad (2.7)$$

$$E_{th\_average} = 2J - E_{consumed\_average} \quad (2.8)$$

This threshold has yielded a lifetime of 127384 cycles using the previous mentioned conditions.

#### 2.3.6.2 The Eth per NM Technique

This NM threshold is based on having a unique NM threshold for each sensor, in order to maximize its energy utilization to the maximum. This method was obtained in [Botros, 2009] by solving simultaneous equations. However, the same method cannot be used in the even-by-event algorithm since it represents a real time application and calculations can't be done beforehand. Since both algorithms are using almost the same parameters, the same threshold vector  $E_{th\_per\_NM}(i)$  calculated in [Botros, 2009] was taken as a reference for the even-by-event algorithm. Since this threshold calculation used in [Botros, 2009] has achieved a better network lifetime than LEACH-C, it was assumed that it might increase the network lifetime in [AbouElSeoud, 2010]. However, while using this  $E_{th\_per\_NM}(i)$  vector, it is very important to ensure that same sensor<sub>i</sub> acting as NM in the Lifetime Optimization algorithm, is the same sensor<sub>i</sub> acting as NM in the event-by-event model. Also, the order of the NMs has to be the same in both scenarios. This threshold was able to increase the network lifetime by 15.4% by achieving 147049 cycles.

#### 2.3.6.3 The Eth Max Technique

The Eth Max technique is based on simply taking the highest value in the  $E_{th\_per\_NM}(i)$  vector and setting this value as a threshold for all the sensors. The highest value will represent the sensor that has consumed the most energy while acting as NM. This means that no other sensor will consume more energy than the one with the highest consumed energy, while acting as NM. Hence, all sensors should consume their energies more efficiently compared to the previous Eth examples. This threshold is calculated as follows [AbouElSeoud, 2010]:

$$E_{th\_max} = 2J - E_{consumed\_max} \quad (2.9)$$

This technique has resulted in a lifetime of 163478 cycles, which is an increase of 11.2% compared to the previous result in  $E_{th}$  per NM technique.

#### 2.3.6.4 The Iterative Search Technique

The iterative search technique is different than the previous threshold techniques. It relies on running several simulations in order to obtain the most fixed threshold for all the sensors that could maximize the network lifetime. The first simulation started by using the  $E_{th\_max}$  calculated from the previous example. Then the threshold was manually increased bit by bit in every simulation, as long as the lifetime value is increasing as well. Once the lifetime value starts to decrease, the simulations should be stopped. This means that the last value that was simulated was the maximum threshold and has increased the network lifetime to the maximum. In this example the iterative threshold that was obtained was  $E_{th\_itr} = 1.54$  and has achieved a network lifetime of 168146 cycles. This has increased the lifetime obtained in  $E_{th\_max}$  by 3%.

#### 2.3.7 NM Threshold Comparison

It can be concluded that the  $E_{th\_itr}$  technique has yielded the highest lifetime value. However, in order to obtain that value, it requires a lot of simulations and a lot of processing that consumes a lot of energy. Therefore, a comparable method that achieves closer results to the  $E_{th\_itr}$  is the  $E_{th\_max}$  technique. This technique will be used for obtaining further NM threshold.



## Chapter 3

### 3 Generalized Electromagnetic Pollution Monitoring using WSN

WSN have been implemented in many applications as a monitoring tool. Some of these monitoring examples are environmental monitoring, office and home automation, traffic control, civil infrastructure, alarm systems, personal health and many others [Mikhaylov, 2012]. In this chapter, a WSN will be used to monitor electromagnetic pollution. Electromagnetic (EM) pollution has recently become a very known term and most importantly a concern for everyone. The fact that the number of smartphones and wireless devices people are currently surrounded by has significantly increased, leads to the exposure of high electromagnetic emissions that are coming out of these devices. These emissions have a dangerous effect on the human's health that in some cases can cause cancer, leukemia or neuropsychological disorders [Das, 2015]. Therefore, the need for monitoring these radiations is essential in order to protect the human's health from getting exposed to these radiations beyond a certain a limit.

In this chapter a WSN-based framework is proposed in order to monitor four frequency polluters and identifies any frequency violation from the four polluters. However, the aim of this model presented here is not only to monitor the frequency pollution, but also to examine the different parameters used in this network and study the effect of changing these parameters to more dynamic ones in order to make this framework more suitable for various applications. Additionally, it is also very important to note that prolonging the network's lifetime is also a very fundamental factor that will be taken into consideration while examining these parameters. The first section will describe the background information on which this proposed algorithm is based on. Then section two describes the proposed randomized model and the three main parameters that affect the network's lifetime. Later, in Section three different random distributions are going to be used for these parameters and their effect on lifetime will be investigated. Finally Section four summarizes the chapter.

### 3.1 System Background

In mobile communication, there is a high demand for building base stations and wireless infrastructures, in order to provide highest data bandwidth and better mobile coverage [Derr, 2015]. However, the drawback of these many base stations is their electromagnetic emissions that are hard to be controlled and could affect the human's health. Also, in some countries, the frequency pollution is not monitored and there are no strict regulations that monitor placing the antennas above the office buildings or the residential houses [Stacenko, 2015]. Additionally, since there are different mobile service providers in each country, it could happen that different base stations can co-exist at the same area and together exceed the maximum allowable EM radiations. Hence, the system presented here is designed based on the model used in [AbouElSeoud, 2010] to monitor the frequency pollution of four different service providers and will be described in details in the next section.

#### 3.1.1 System Model Architecture

The wireless sensor network system model designed in [AbouElSeoud, 2010] consists of 100 narrow band sensors that are uniformly distributed across the  $100 \times 100 \text{m}^2$  area in order to cover the whole area and, at the same time, suit the commonly used applications. As mentioned in the previous chapter 2 four frequency polluters are placed at the four sides of the area and for each frequency polluter there are 25 sensors dedicated to it as shown in Figure 3.1. The sensors are placed in an ordered manner so that the 25 sensors of each frequency polluter are distributed uniformly over the  $100 \times 100 \text{m}^2$  area. These 25 sensors should sense the frequency violation occurring from their associated frequency polluter. However, since in this example the transmission energy is fixed, it is assumed that only half of the 25 sensors in each area will sense the violation. This half or 11 sensors will represent the closest sensors out of the 25 sensors to the frequency polluter. In case of changing the transmission power of the frequency polluters in the future, the number of sensing sensors can be then changed accordingly.

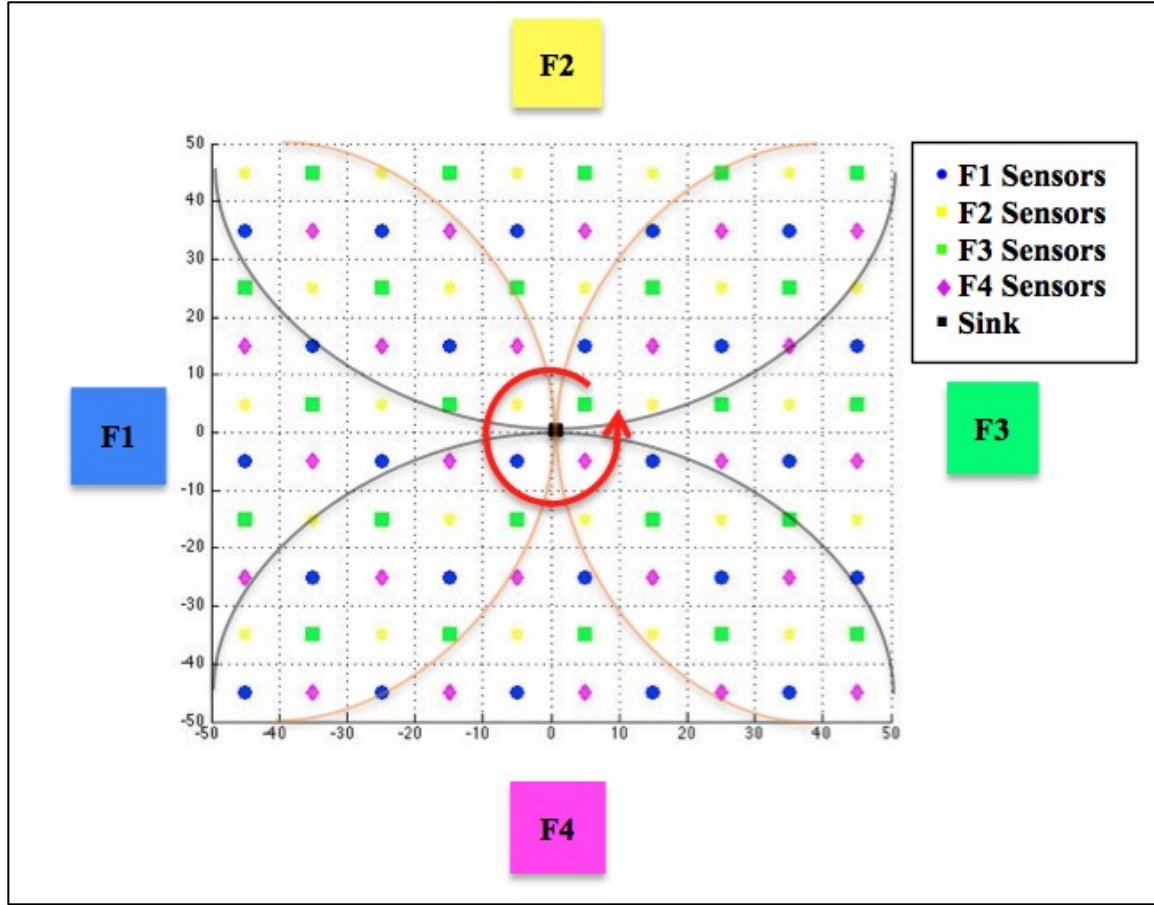


Figure 3-1 Placement of wireless nodes that correspond to each frequency polluter and the red arrow illustrates the circular path of the NM selection.

As previously mentioned in chapter 2 the event-by-event algorithm used in [AbouElSeoud, 2010] relies on a specified violation schedule, where every day a single frequency polluter breaches the EM level for six hours. It starts by polluter F1 that violates the EM level for six hours starting from 6pm till 12am on the first day and end by F4 violating at the same times on day 4. This process repeats itself every four days. This specified schedule has caused the algorithm to be limited and not to have room to accommodate dynamic network change. Henceforth, the aim of the introduced generalized framework here is to convert the event-by-event algorithm to a more dynamic and flexible one that could easily adapt to diverse network changes and also be applicable to a wider scope of assumptions and applications. The generalized system model relies on the same parameters used in [AbouElSeoud, 2010, Heinzelman, 2000 and Nough, 2010].

Additionally, there are three fixed main parameters that the event-by-event algorithm relies on. The first parameter is the starting time of the violation, which is at 6pm everyday. The second one is the duration of the violation, which is six hours. Last but not least, is the number of violators per day that is assumed to be one per day. In the proposed algorithm, random variables are going to be used for each of those parameters, which will be described in details in the following sections.

## **3.2 The System's Main Parameters**

### **3.2.1 The Starting Time**

The starting time parameter resembles the starting time of the violation, which was assumed in the event by event algorithm to be at 6pm every day. In the proposed algorithm, this parameter was selected to be a random variable between 12am and 6pm using uniform distribution. Since the violation duration is maximum six hours, the last starting time has to have at least a six hour range till midnight in order not to extend over the next day. That's why 6pm will be the last starting time for the random variable range. In MATLAB, a stream of random numbers from 1 till 19 was generated for every polluter in order to represent the starting time, where 1 and 19 correspond to 12am and 6pm respectively. Different random distributions could be used in generating these random numbers such as uniform, Gaussian and exponential distribution. Later, the results of these different distributions will be demonstrated and compared to each other.

### **3.2.2 The Violation Duration**

As previously mentioned, the violation duration in the event by event algorithm was assumed to be six hours. Hence, in order to make this assumption more flexible, one will generate a random number between one and six in order to represent the violation duration. This means that the polluter could violate for a minimum of one cycle and a maximum for 6 cycles, because it is still tied by the event-by-event general assumptions. However, the main reason for proposing this generalized algorithm is to show some flexibility in the parameters and their effect on the network and at the same time make them accommodate various expectations. Later, the same idea could be implemented on

other rigid systems that also rely on fixed parameters and the effect of having random parameters in that case, could be examined.

### 3.2.3 Number of Polluters per Day

In [AbouElSeoud, 2010], each polluter was supposed to violate alone on each day, meaning that on day one F1 will violate, day two F2, day three F3 and day four F4. This process repeats itself again every four days. Since this parameter is fixed to one polluter per day, it was suggested in the proposed algorithm to make this parameter more flexible and enable it to accommodate more than one polluter per day. This means that having the number of polluters as a random variable will allow the system to either have one, two, three or even four polluters violating on the same day. They don't have to necessarily violate at the same time or for the same duration period, then this will depend on the previous parameters, which are the starting and the violation duration of each polluter. Moreover, depending on the number of polluters violating on the same day, different polluters' combinations will occur. For instance, if the number of polluters per day came out randomly to be two, then there will be different combinations of two polluters together out of the four, which are: F1 and F2, F1 and F3, F1 and F4, F2 and F3, F2 and F4 or F3 and F4. These combinations could be calculated as follows:

$$C_r^n = C_2^4 = 6 \text{ combinations} \quad (1)$$

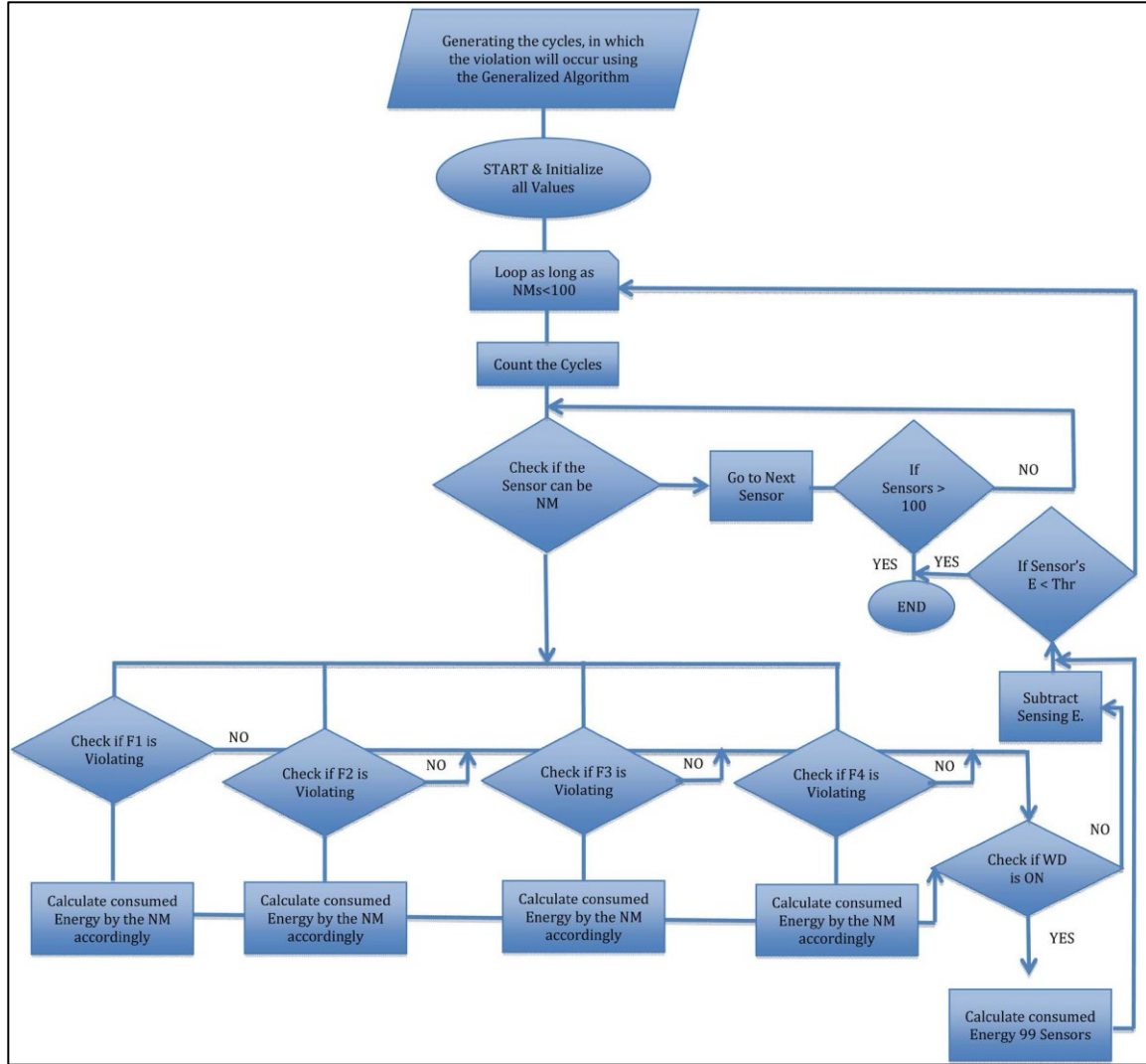
where n is the total number of polluters and r is the number of polluters violating on the same day. Henceforth, if there are three violators breaching the specified EM level on the same day, there will be  $C_3^4 = 4$  possible combinations of random polluters per day. Therefore, the number of polluters per day random variable should as a first step select the total number of polluters violating on the same day. Afterwards, it should also randomly select one of the possible polluter combinations, when one, two or three polluters violating per day are randomly selected first. Using this method will guarantee the uncertainty of knowing violating polluters ahead, which in real life is the case, as no one can predict which polluter will violate beforehand.

Combining all three parameters together and making them all random at the same time will allow this algorithm to be more flexible and be suitable to different applications. This will be discussed thoroughly in the next section.

### **3.3 Using different Random Distributions for the Three Random Variables**

The main advantage of the Generalized algorithm that is proposed here is the ability of combining the previously mentioned parameters as random variables all together at the same time. This means that according to the desired requirements, one can choose which parameters should have a random variable and which one should not, for example an application could require having the starting time and violation duration to be random, while the polluter is a single one, so in this case the number of violating polluters is fixed. Hence, it is always possible to have different combinations of random or fixed variables that could simulate varied real life examples.

Additionally, different random distribution will be introduced, where each parameter has the possibility of choosing a different random distribution than each other depending on the desired application. This adds further flexibility to the proposed system and allows the parameters to demonstrate real applications. The different random distributions are the uniform, Gaussian and exponential distribution. For simplicity the uniform distribution will be selected as the default random distribution, in order to have a common base for comparison. The next Figure 3-2 shows a flowchart that describes the workflow of the Generalized Framework in details. Later, in the next section, different scenarios will be tested in order to show the usage of this new algorithm.



**Figure 3-2 Flowchart of the Generalized Framework.**

### 3.3.1 Examined scenarios

In this section, different scenarios will be examined in order to demonstrate the Generalized algorithm capabilities. The main aim of this algorithm is to turn the system model used in [AbouElSeoud, 2010] into a more generic one that could easily model various scenarios and applications. The first scenario that will be used here is the original scenario described in [AbouElSeoud, 2010]. As mentioned before, this scenario assumes that there are four violators on each side of the monitored area, and each one of them is violating for six hours on a separate day starting by F1 and then going in order till the

fourth polluter is reached and then the process repeats itself every four days. This original scenario will be used here as the default model or base scenario, where other results obtained from different scenarios will be compared to that one in order to have a fair comparison. When this scenario was applied to the generalized framework using Matlab [MATLAB] simulations, it yielded a lifetime value of 162296 cycles. This result will be referred to as the default lifetime value.

The first common scenario that will be examined using the proposed algorithm is having the four polluters violating on the same day at the same time. In this scenario F1, F2, F3 and F4 will violate on the same day, while all the other parameters will remain constant, which are:

- Starting time of the violation = 6pm.
- Violation Duration = six hours.

This results in a lifetime value of 122977 cycles, which is a 24.227% decrease compared to the default model. One would expect that having four polluters violating on the same day would cause the network lifetime to drop instantly by 75%. However, this is not the case due to many reasons. The first one is using the watchdog technique. So whether there is a violation or not, each sensor should send an “I’m alive” packet to the current NM every 3 cycles. These packets are of same size as the packets that are sent when there is a violation; hence they consume the same energy. So, when there is a violation, there will be no need to send an extra packet to indicate that the sensor is alive, as it is already communicating with the chosen NM. The second reason is the number of NMs in each simulation and accordingly the energy consumption during the cycles of these simulations. In the default model there is only one polluter per day and only 11 sensors are sending packets to indicate the violation. However, in the other case, where four polluters are violating at the same time, there are 44 sensors reporting the violation. Hence, the energy consumption is not evenly distributed since it relies on the location of the current NM and also on the distance between the NM and the sensors that are reporting the violation. All this achieves only a 24.227% lifetime decrease compared to the default model instead of 75%. The results show that having the four polluters violate



at the same time will not cause the energy consumption to be four times the single polluter that is violating; however, it will be much less due the previously mentioned reasons.

In the following sections, all the three fixed parameters will be considered as random variables and their effect on lifetime using different random distributions for each one of them will be examined. This will allow indicating the parameter for which the variance has a significant effect on the lifetime.

### 3.3.2 Effect of Starting Time Randomness on Lifetime

The first parameter that will be examined is the starting time of the violation. As mentioned before, when converting the starting time parameter to a random variable, a stream of random numbers between (1-19) will be generated in order to represent the starting time values, where the number 1 and 19 represent the time 12am and 6pm respectively.

**Table 3-1 Starting Time Mapping to Random Variables**

Random Variable	Actual time	Random Variable	Actual time
1	12am	11	10am
2	1am	12	11am
3	2am	13	12pm
4	3am	14	1pm
5	4am	15	2pm
6	5am	16	3pm
7	6am	17	4pm
8	7am	18	5pm
9	8am	19	6pm
10	9am		

The uniform random distribution will be used to generate the stream of random variables for the starting time. The other two parameters will remain constant in order to be able to compare the results with the default mode. They will have the following assumptions:

- Violation Duration = six hours.
- Number of polluters violating per day = one.

This experiment has produced a lifetime value of 162304 cycles, which is only 8 cycles more than the default lifetime. This increase is equivalent to 0.0049%, which shows that having the starting time parameter as a random variable has an insignificant on the network's lifetime, which in other words means that it doesn't really matter when the violation starts. It has the same effect at the end.

### **3.3.3 Effect of Number of Polluters vs. the Duration Randomness on Lifetime**

The previous section has proven that the starting time as a random variable does not have a significant effect on the network's lifetime. Therefore, it will remain a fixed parameter as in [AbouElSeoud, 2010] and the other two parameters will be compared together, in order to obtain the parameter with the most effect on the network's lifetime. When comparing between the violation duration and the number of polluters violating per day, two scenarios will be simulated. The first one is Scenario (a), which relies on fixing the number of polluters per day; in case A: only F1 will violate, case B: F1 and F2 will violate, case C: F1, F2 and F3 will violate and finally in case D all polluters will violate on the same day. On the other hand, the violation period will be a random number between (1 - 4) that is uniformly distributed in all four cases. The reason why only this range is selected and not from (1 – 6) cycles as previously used in [AbouElSeoud, 2010], is due to the fair comparison that should occur between the number of polluters and the duration variables. Hence, both of them have to produce a random number between 1 and 4. The results of (a) are indicated in the next Table 3-2.

**Table 3-2 Scenario (a): Fixed No. of Polluters vs. Random Duration**

Fixed No. of Polluters vs. Random Duration		
		Duration
Cases	No. of Polluters per Day	U (1,4)
A	F1	162470
B	F1, F2	160973
C	F1, F2, F3	160373
D	F1, F2, F3, F4	158849

The results obtained in Table 3-2 show that changing the number of polluters from (1,4) does not have a noteworthy effect on the network's lifetime value. Comparing the lifetime output values together, they only differ by 0.01% to 2.2%. This also proves why, in Section 3.3.1, having four polluters violating everyday does not drop the lifetime by 75%, but instead it only decreases by 24.227%. Therefore, it is very important to repeat this experiment in Scenario (b) but by switching the variables. The violation will have then fixed values from (1,4) separated in four different cases and on the other hand the number of polluters per day will be a uniformly distributed random value from (1,4). The next Table 3-3 will demonstrate the results of Scenario (b).

**Table 3-3 Scenario (b): Fixed Duration vs. Random No. of Polluters**

Fixed Duration vs. Random No. of Polluters		
		No. of Polluters
Cases	Duration per cycle	U (1,4)
A	1	181799
B	2	168117
C	3	150278
D	4	150242

It is obvious that in Scenario (b), the duration variable has a significant effect on lifetime. When Case A, where (1,4) polluters are violating everyday for one hour, is

compared to the default lifetime, it shows that it has increased the lifetime by 12.02%. The reason for that the sensors sensing the violation for one cycle will for sure consume less energy than the sensors sensing the violation for several cycles and sending their sensed data to the NM. Moreover, when all four cases A, B, C and D are compared together; they result in a change in lifetime between 7.53% and 17.36%. This shows that varying the duration from (1,4) simply has a notable effect. Additionally, out of the three parameters, the violation duration is the only parameter that affects the lifetime the most.

### 3.3.4 Effect of changing Random Distribution on lifetime

Since the results of the previous section in Scenario (b) have shown that varying the duration parameter has a huge effect on lifetime, it is very important to investigate applying the duration as a random variable, while using different random distributions, in order to investigate the effect of the different random distributions. Therefore, Scenario (a), where the number of violators is fixed per day and the duration is a random variable, will be applied again. However, Gaussian and exponential distributions will be used as random distributions, in addition to the uniform distribution results that were obtained in Scenario (a). The next Table 3-4 shows the outputs of the different random distributions all together used for the duration random variable.

**Table 3-4 Scenario (c): Using Different Distributions for Duration Random Variable**

Using Different Distributions for Duration Random Variable				
Cases	No. of Polluters per Day	Duration		
		U (1,4)	N (2,0.5)	Exp (2)
A	F1	162396	167245	171968
B	F1, F2	160973	167297	169991
C	F1, F2, F3	160373	163749	166271
D	F1, F2, F3, F4	158849	162344	165410

Since every random distribution has different input parameters, it is very hard to compare them together. However, for fair comparison, the same mean has been used in

all three distributions. The results show that the Gaussian distribution has achieved a slightly higher lifetime value than the uniform distribution, while the exponential distribution has yielded a much higher lifetime value than both of them. The reason for that is that in the exponential distribution the probability of reaching the high values of the duration variable is much less than the low values, hence it results in a higher lifetime since the duration variable is always at minimum. When comparing the exponential distribution results to the uniform distribution ones, it shows that the lifetime value has increased by a factor of 3.97% to 5.57%. In fact this increase is not very significant and the reason for that is due to the small range of random variables, which only varies between 1 and 4. Hence, there is a need of extending the random variable range more, in order to obtain a more accurate comparison between the different random distributions. This will be investigated next.

### **3.3.5 Effect of Changing Random Distributions on Lifetime with a Wider Range of Variables**

In this example, a fourth scenario (d) will be implemented, which will be base on Case D in Table 3-4. In order to obtain a wider range of variables for the duration parameter, the starting time of the violation has to be changed from being at 6pm to 1am. When the violation starts at 1am, meaning at the beginning of the day, the polluter will then have more hours till the end of the day to violate at, without crossing over the next day hours. Hence, the duration will be a random variable the lies between (1,23) and accordingly the random distributions will be tested using the wider range. The next Table 3-5 shows the outputs of this experiment.

**Table 3-5 Scenario (d): Using Different Distributions for Duration Random Variable**

Using Different Distributions for Duration Random Variable				
		Duration		
Cases	No. of Polluters per Day	U (1,23)	N (11,0.6)	Exp (11)
D	F1, F2, F3, F4	92111	95278	105972

The outputs of scenario (d) illustrate the same trend as the previous results in

scenario (c). It is clear that the uniform distribution has the lowest lifetime value compared to the Gaussian and exponential distribution, while the exponential distribution has achieved highest lifetime compared to the other two for the same reason that was mentioned in the previous section. The Gaussian distribution is very close to the uniform distribution, especially when they share the same mean. Therefore, the Gaussian distribution lies in the middle between the uniform and the exponential distributions; however it tends to be closer to the uniform distribution, as it has increased the uniform lifetime value by only 3.4%. On the contrary, the increase in lifetime from the uniform to exponential distribution is about 13.08%, which is more than a double increase, when comparing it to the previous scenario (c) that was max 5.57%. This proves, that having a wider range of random variables has revealed the real effect of changing the random distribution on the duration parameter. However, this does not mean that the exponential distribution is the best distribution to be chosen for the duration random variable. Selecting between different random distributions will always rely on the application requirements and assumptions. Additionally, the Generalized algorithm demonstrates how flexible it is, by switching between fixed and random variables and also between different random distributions.

### 3.4 Chapter Conclusion

Wireless Sensor Networks are used in a variety of applications, especially the ones that require monitoring and tracking. Therefore, WSN could be one of the successful models that could monitor the EM pollution. However, due to the rapid changed requirements and assumptions, it is very hard to use a monitoring system that has fixed variables that hardly could accommodate the up to date conditions. Therefore, there was a need for implementing a more generalized algorithm that is based on the EM monitoring system developed in [AbouElSeoud, 2010] in order to accommodate the different life changing requirements. The main parameters in the previous system, which are the starting time, the violation duration and the number of polluters violating per day, are treated as random variables in the new framework and their effect on the network's lifetime, was also investigated.

In order to further demonstrate the use of the Generalized algorithm, several use cases have been implemented to that system. The output of the simulated scenarios has shown that the duration of the violation has the most effect on the network's lifetime, and accordingly it can increase the network's lifetime between 7.53% and 17.36%. On the contrary, the rest of the parameters do not have a significant effect on lifetime like that. Furthermore, the effect of changing the random distributed was also investigated through simulating different scenarios. Applying the uniform, Gaussian and exponential distribution on the duration random variable, the exponential distribution has yielded higher lifetime value compared to the other two. Comparing the exponential distribution to the uniform distribution the exponential distribution has prolonged the network's lifetime by 13.08%. However, this does not mean that using the exponential distribution is better than using the uniform or the Gaussian distribution. It all depends on the application and its requirements, and accordingly selecting the most adequate distribution that matches those. Finally, the simulations have also shown that having a wide range of variables in each of the random parameters is very essential, as it will always yield better and more accurate results when comparing those parameters together.

In Chapter 3, the main aim was to develop a generalized algorithm and accordingly obtain the most effective parameters in it. Although it showed that manipulating some parameters and using different random distributions could affect the network's lifetime, still there was no intention of prolonging the network's lifetime. The only concern was that working on the system model developed in [AbouElSeoud, 2010] could be a bit limited to certain applications and to certain assumption. Therefore, there was a need for generalizing these assumptions, in order to make sure that the fixed assumptions that were used are not the specific and could be implemented on other applications as well. Nevertheless, since the WSN suits a lot of applications and could be implemented anywhere, there is always a need of sustaining this network at the maximum. Thus, Chapter 4 will concentrate on prolonging the network's lifetime using the same system model in [AbouElSeoud, 2010]. However, other network parameters that are also fixed will be examined further in order to investigate if manipulating them could extend the network's lifetime.

# Chapter 4

## 4 On the Impact of the Death Criterion of the WSN Lifetime

As previously mentioned, WSN are used in various critical applications and hence require a network that could sustain for a longer lifetime. Since the WSN network relies on sensors that are battery operated, this means that the network's energy has to be efficiently consumed in order to be able to maximize its lifetime. Henceforth, in this section a modified NM threshold calculation will be introduced. Moreover different death criteria will be studied in order to identify the most adequate criterion that could prolong the network's lifetime the most. Additionally changing the number of cycles per NM will be investigated and finally the approach of choosing the NM will also be examined.

### 4.1 System Architecture

#### 4.1.1 System Model Design

The WSN network that will be used in studying all the previous points is the same system model that was used in [AbouElSeoud, 2010]. This system consists of 100 sensors that are uniformly distributed in a  $100 \times 100 \text{m}^2$  area in order to measure the various frequency radiations within this area. Four frequency polluters are placed at each side of the area and accordingly the network area is divided into four subareas  $F1_{\text{Area}}$ ,  $F2_{\text{Area}}$ ,  $F3_{\text{Area}}$  and  $F4_{\text{Area}}$ , where each of those subareas consists of 25 sensors as illustrated in Figure 4-1. Each group of the 25 sensors is associated to a single frequency polluter and should report any frequency violation coming from this specific frequency polluter. However, for simplicity, it was assumed that the frequency polluter range would only cover the 11 sensors that are placed closely to the polluter, which is almost half of the 25 sensors. This radiation range could be easily adjusted further according to the different WSN applications. Furthermore the sink that aggregates the data from the Network Masters (NMs) is placed at the center of the network, since in [Nouh, 2010] this location has proven to be the best location in terms of energy usage and network lifetime. The



same parameters used in [AbouElSeoud, 2010, Heinzelman, 2000 and Nough, 2010] and also in chapter 3 will be used here as well.

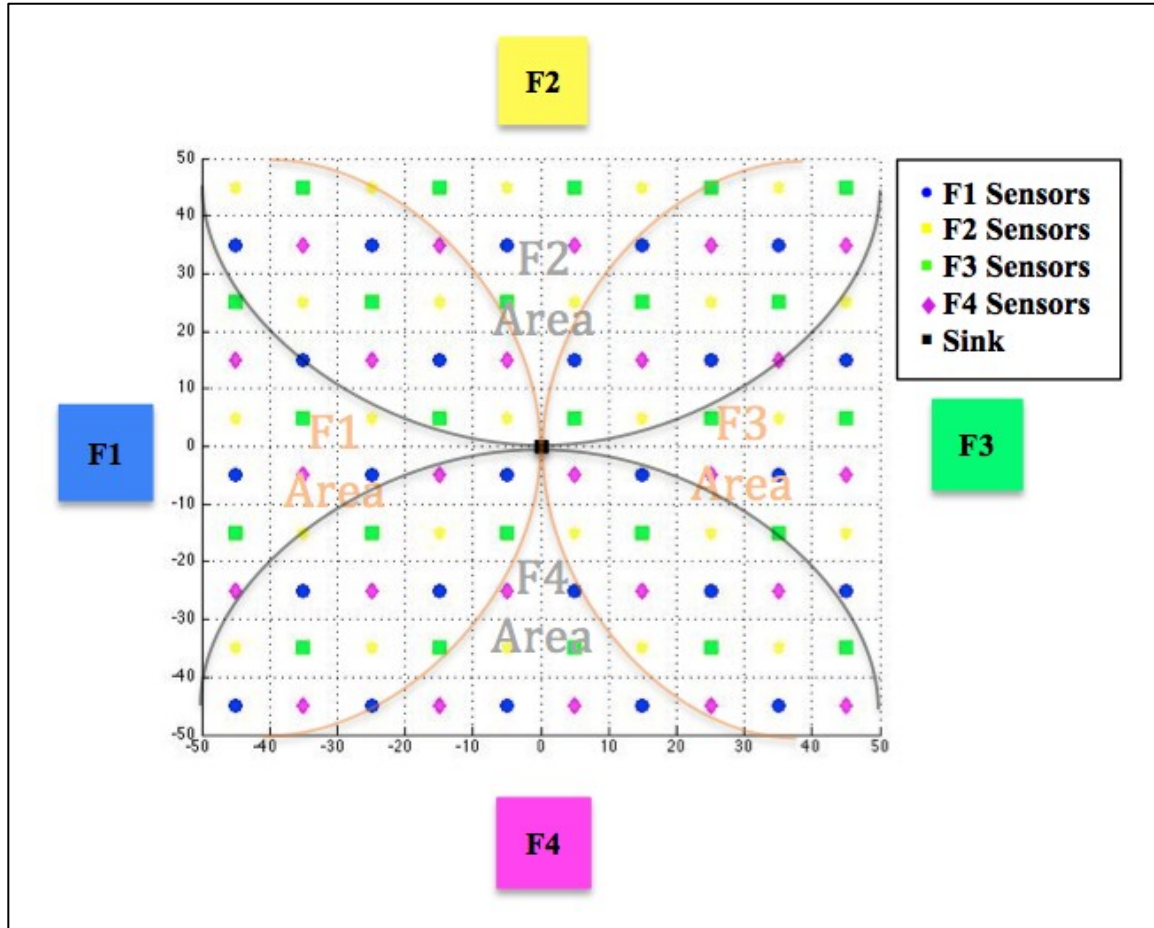


Figure 4-1 100 uniformly distributed sensors in a  $100 \times 100 \text{ m}^2$  area & surrounded by four polluters

#### 4.1.2 The Monitoring Process

In [AbouElSeoud, 2010], the above-mentioned system model was used while applying a specific monitoring process. This same monitoring process that was also used in the previous section will be applied here as well, in order to have a common base for comparison. This monitoring process requires that each frequency polluter, starting with polluter F1, should violate or exceed the required transmitted frequency during the last six hours of the day; however, only one polluter is allowed to violate per day. Likewise in [AbouElSeoud, 2010], an hour is defined as one cycle, in order to be able to easily simulate it on Matlab [MATLAB]. During this cycle, one of the 100 sensors is chosen to act as an NM and hence receives the data from all 99 sensors, aggregates it and sends it

back to the sink. The process of selecting the NMs is the same one used in [AbouElSeoud, 2010 and Nouh, 2010], where the NMs are selected in a circular path starting by the closest sensor to the sink. In order for a sensor to act as an NM, it has to hold a minimum amount of energy that enables it to receive data from the rest of the sensors and sends it back to the sink. This amount of energy is known as the NM threshold, which was introduced in details in the literature review section and will be discussed next in more details.

#### 4.1.3 NM Threshold

The NM threshold is the minimum energy required by the sensor to receive packets from 99 sensors, aggregate the data and send it back to the sink. The calculation of this threshold is based on the distance between the NM sensor and the sink and also between the NM sensor and the rest of the sensors. A similar approach for calculating the threshold is also defined in [Botros, 2009]. The threshold computation happens only once at the sink and prior the beginning of the monitoring process reducing the network running overhead. The reason for that is that the calculation mostly relies on the sensors' locations, which are already known from the start. Henceforth, each sensor will have its own pre-calculated NM threshold that will allow it to act as a NM for several cycles. These cycles are then counted during the monitoring process. The equation that is used to calculate the NM threshold for each sensor is as follows:

$$E_{threshold\_NMi} = E_{rx} \times N_s + E_{agg} \times K \times N_s + E_{prot} + E_{tx} \quad (4.1)$$

$$for i = 1, 2 \dots 100$$

$$where: \quad E_{rx} = E_{elec} \times K \quad (4.2)$$

$$where: \quad E_{tx} = E_{amp} \times K \times D_{NM to sink}^n \quad (4.3)$$

The  $N_s$  parameter that is mentioned in Eq. 3.1 is the number of sending nodes, which in this case is 99, because the 100<sup>th</sup> is the NM. Additionally, the  $D_{NM to sink}$  in Eq. 3.3 is the calculated distance between the  $i^{th}$  NM and the sink.

After the NM reaches the previously illustrated threshold, it starts to act as an active sensor. The next sensor inline is examined to determine whether it is above the specified threshold or not in order to act as a NM. If it happens and the remaining energy of the current sensor is actually below the NM threshold, then the following sensor will be examined and so on till the 100<sup>th</sup> sensor is reached. Meanwhile the rest of the sensors are acting as active nodes, meaning that they are sensing the violation, when one exists, and sending their data to the current NM. They also have a known active node threshold that was also defined in [AbouElSeoud, 2010], which is the ability of a sensor to sense and send packets to the NM. If the energy of the sensor goes below that active node threshold, then the sensor will be considered dead. Moreover, if there is no violation, the active node has to send an “I’m alive” packet every predefined number of cycles, in order to notify the NM that it is not dead. The process of sending the “I’m alive” packets is called the watchdog technique that was previously explained in the literature and the predefined number of cycles is chosen to be every 3 cycles as in [AbouElSeoud, 2010]. The lifetime of the whole WSN network relies on the percentage of active sensors. Previously in [Botros, 2009; Nouh, 2010; AbouElSeoud, 2010], this percentage was considered to be 100%. This means that if only one sensor is below the active node threshold, then this sensor is considered dead and henceforth the whole network will also be dead and will stop functioning. The drawback of this 100% is that the network might still have some remaining energies in other sensors that could enable it to live for a longer time. However, it has to stop due to the death of one single node. Therefore, this percentage will be investigated further in the next section by examining the death of multiple nodes at the same time and their effect on the network lifetime.

## 4.2 Network Death Criteria

In many previous sources [Mahfoudh, 2008; Heinzelman, 2000; Mamun, 2010], the network lifetime was defined as the time till the failure of the first node. This network lifetime definition was not energy-efficient, since there were other sensors in the network that still possess sufficient remaining energy that could enable them to perform their functions and sustain the network for a longer lifetime. Henceforth, there is a need in

exploiting the remaining energy of the network. This could happen by allowing more than one sensor to fail at the same time without affecting the functionality of the network and at the same time keeping the network alive. The proposed definition of lifetime will depend on the needed information from the sensors' readings aggregation process, which sense the same phenomena [Chen, 2009]. The first definition, which is the original lifetime definition used in [Mahfoudh, 2008; Heinzelman, 2000; Mamun, 2010], is based on ANDing all the sensors' measurements'. Hence, as mentioned before, this will require all the nodes to be alive because in case of one node failure, the whole network will be considered dead. Moreover this definition is in fact not very practical, because the death of a single node does not prevent the rest of the nodes from performing their functionalities, due to the architecture of the deployed nodes within the network and also the self-organizing and fault tolerance capabilities that the network owns [Hang, 2009]. The second definition is based on the OR rule, which is defined as at least one sensor is still alive. The third definition will be the Majority rule, which is at least half of the sensors are alive in order for the network to stay active. These three death criteria definitions will be studied further, in order to obtain their efficient use of the node's remaining energy and their impact on the network.

#### **4.2.1 The AND Rule**

As mentioned before, the AND rule is the legacy rule, which depends on the death of the first node. Once it is dead, the whole network will stop functioning. The idea was obtained from using the logical AND gate, where all the input values have to be true, in order for the output to be true as well [Mano, 2014]. Figure 4-1 shows that the network area is divided into four subareas. Each subarea contains 11 sensors that are associated to the nearby frequency polluter. Those 11 sensors keep sensing if there is any frequency violation and send their packets to the current NM as explained in the previous section. Hence, they are acting as active nodes, unless one of them is the NM. Once the remaining energy of one of those 11 sensors has reached the active node threshold, then this node will be considered dead and so will be the area where that sensor is located and also the whole network. Still the rest of the sensors could have some remaining energy that could enable the network to survive for a longer period of time. But in some critical

applications the death of a single node cannot be tolerated; such as health monitoring applications [Silva, 2010], where the patients are monitored inside a hospital or in fire fighting situations [An, 2011]. This is where the 1st definition of lifetime will be used, especially when the network is easily accessible and the sensors can be replaced. Therefore, other solutions should be obtained in order to sustain the network as much as possible

#### **4.2.2 The OR Rule**

The definition of the OR rule is also driven from the logical OR gate [Mano, 2014]. It is described, as at least one sensor within the subareas  $F1_{Area}$ ,  $F2_{Area}$ ,  $F3_{Area}$  and  $F4_{Area}$  shown in Figure 4-1 is active to sense the violation from its associated frequency polluter. Once the 11 sensors in one of those subareas have reached the active node threshold, then this area will be considered dead and accordingly the whole network. The advantage of this network lifetime definition is that it exploits the sensor's energy to the maximum, and hence efficiently consumes the whole network's energy. Moreover, WSN are placed in hardly accessible areas like monitoring underwater pipelines [Benhaddou, 2015], mines detection or earthquake prediction [Kisseleff, 2016]; it is very useful to apply this definition. The reason for that is that no need to change the sensor promptly when it fails. The network will keep functioning for a long time till most of the sensors are already dead. At that point you will have to replace the whole network, which might be cheaper than replacing each sensor at a time.

#### **4.2.3 The Majority Rule**

The Majority rule is the middle rule between the AND and the OR rule. In this criterion, the death of approximately half of the sensors per subarea could be tolerated. This means that, out of 11 sensors per subarea, six could fail and then the subarea will be considered dead. As previously explained, when one of the subareas is dead, then the whole network turns out to be dead as well. The Majority rule as well as the OR rule have a notable advantage when compared to the AND rule. The fact that both rules allow the death of more than one node at the same time permits the network to be fault tolerant.

When wireless sensor networks are placed in extreme environments, with harsh conditions, such as placing them in an outdoor environment in the United Arab of Emirates, where the temperature and level of humidity and dust is extremely high [Venkatachalam, 2007], it is very likely that one of the sensors could fail at any point of time, without even reaching the active node threshold. In that case, it is more applicable to either use the Majority or the OR rule, in order to get use of the network's energy, in addition to taking the needed precautions to protect the sensors from failing. Otherwise, the network will stop functioning, even though all the sensors still possess enough energy to perform their required functions.

After describing the three network lifetime criteria, it is very hard to try to obtain which definition is best, since each one of them is more suitable to a different group of applications. Therefore, deciding on which criterion to be chosen will be highly dependent on the application used and the needed network lifetime for that application. Using the previously explained system model in section 4.1, all three network-lifetime definitions will be simulated on Matlab [MATLAB]. Figure 4-2 will give an overview on the results of these simulations. It shows the lifetime span of each subarea in the network, while using each of the above mentioned lifetime definitions.

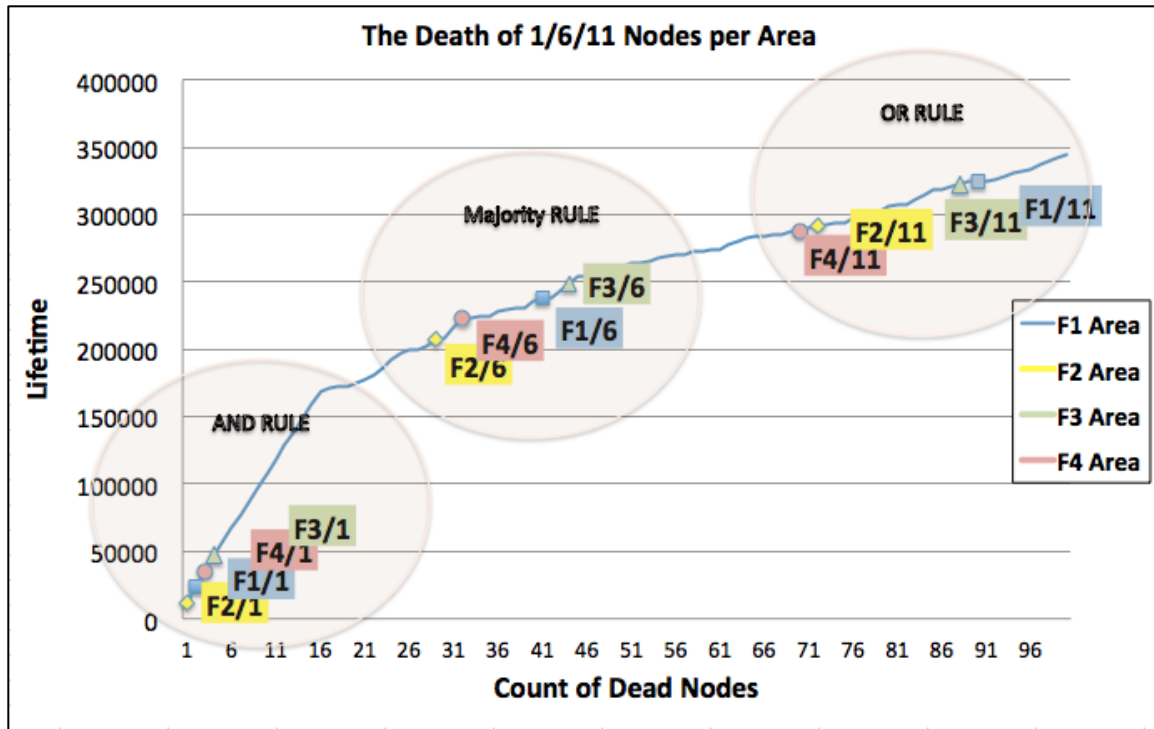


Figure 4-2 The different death criteria are illustrated by showing the lifetime with respect to the number of dead nodes.

The first group of subareas at the bottom left of Figure 4-2 shows the death of the first node in each of those subareas. It also indicates the corresponding lifetime value at which the first sensor dies. For instance, the first sensor that will die in this network will be one of the 11 sensors from subarea  $F2_{Area}$ . The four points in the middle of the graph show the lifetime value after the death of six nodes in each subarea. This should represent the Majority rule, where almost half of the sensors are still alive. Finally, the last four points represent the OR rule, where at least one sensor is alive. Each of those points illustrates the death of the last node in each subarea and accordingly the lifetime cycle at which this sensor dies. Comparing the three criteria together, Figure 4-2 shows that in each criterion, the order of the subareas is different. This means that even though in the first definition the subarea  $F1_{Area}$  dies in second place, this does not assure that this same subarea will also have the second death order in the second or third definition. In the Majority rule, the subarea  $F1_{Area}$  dies in third place, while in the OR rule  $F1_{Area}$  has the highest lifetime and is the last to die. The reason for that is that the death of each node mostly depends on the location of the node and also on the location of the NM.

Depending on that, the internal energy of each sensor is depleted respectively. Therefore, this graph is very important to show the difference between all three definitions. Moreover, according to the required application, one can simply choose from the graph the most adequate network lifetime criteria with regard to the needed number of nodes functioning in the network and also lifetime value. One could also specify the subarea within each death criterion and accordingly the lifetime value at which he/she wants the network to end.

During the previous simulations, a sensor used to act as a NM for numerous cycles till its energy reaches the NM threshold. The number of cycles only depends on the energy that the sensor possesses since it started to act as an NM. There might be a drawback in this approach, which is depleting the sensor's energy all at once, so that when a farther sensor starts to act as a NM, this node will reach its active node threshold very fast and will stop functioning. As the goal of prolonging the network lifetime always exists, in the next section the network parameters are examined further by modifying the number of cycles per NM and observing their effect on the three death criteria and also on the network lifetime.

### 4.3 Impact of the Number of Cycles per NM

#### 4.3.1 Selecting a Fixed Number of Cycles per NM

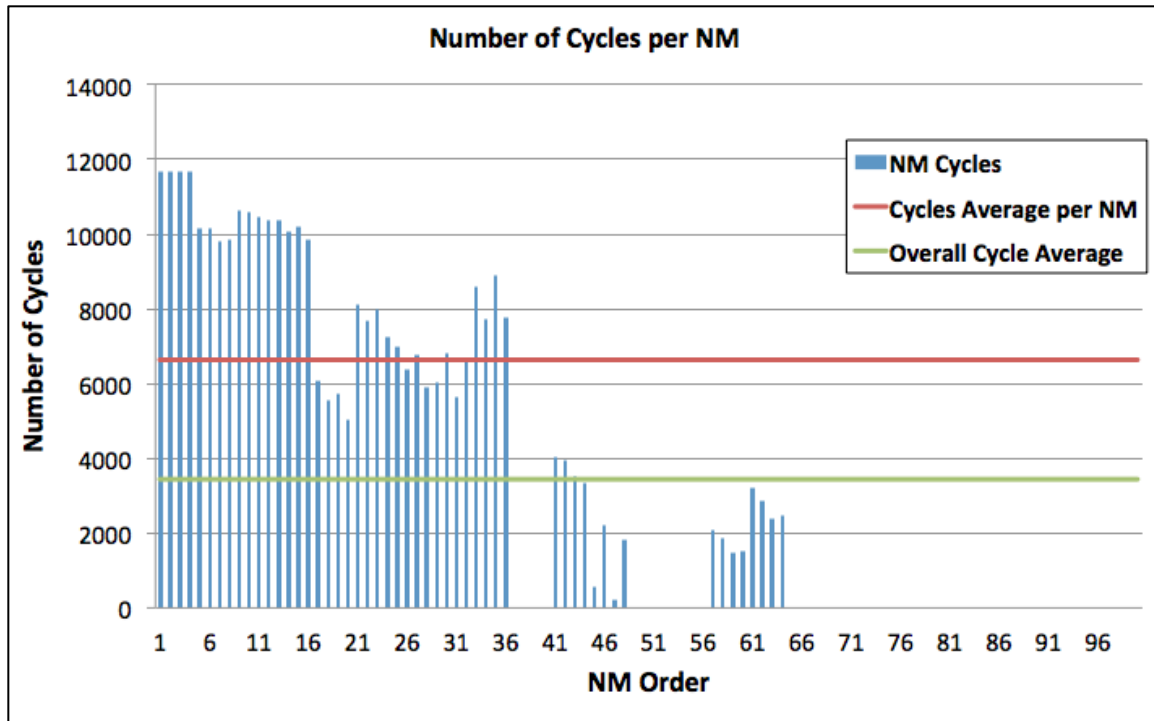
The process of selecting the NM is, as mentioned before, an organized selection that starts by the closest sensor to the sink. This means that the sensors are placed in the network in a circular order around the sink, so that each sensor becomes the NM in its own turn. This happens by first assessing the energy of the sensor and whether it is sufficient to enable it to act as an NM or not. If this is true, then the sensor starts acting as NM for several cycles until it reaches the NM threshold  $E_{threshold\_NMi}$ . If it is not true, then the next sensor inline with sufficient energy will be selected as the NM of the next round. The number of the cycles per NM  $C_{NMi}$  is counted during the ongoing process and hence varies from one NM to the other depending on the original energy that it held when it started to act as an NM. Therefore, in this section, setting a predefined number of cycles per NM will be studied. A similar idea of having a fixed number of cycles per NM was



previously introduced in [Botros, 2009]; however, it was intended to solve the drawbacks in [Heinzelman, 2000 & 2010]. Thus, it was not applicable here to the system model under study. In this model, three different sets of cycles will be examined separately on each death criterion. Every NM is required to act as an NM for that specified set as long as it does not reach the NM threshold. The three sets are:

- 100 cycles per NM round
- 1000 cycles per NM round
- 10000 cycles per NM round

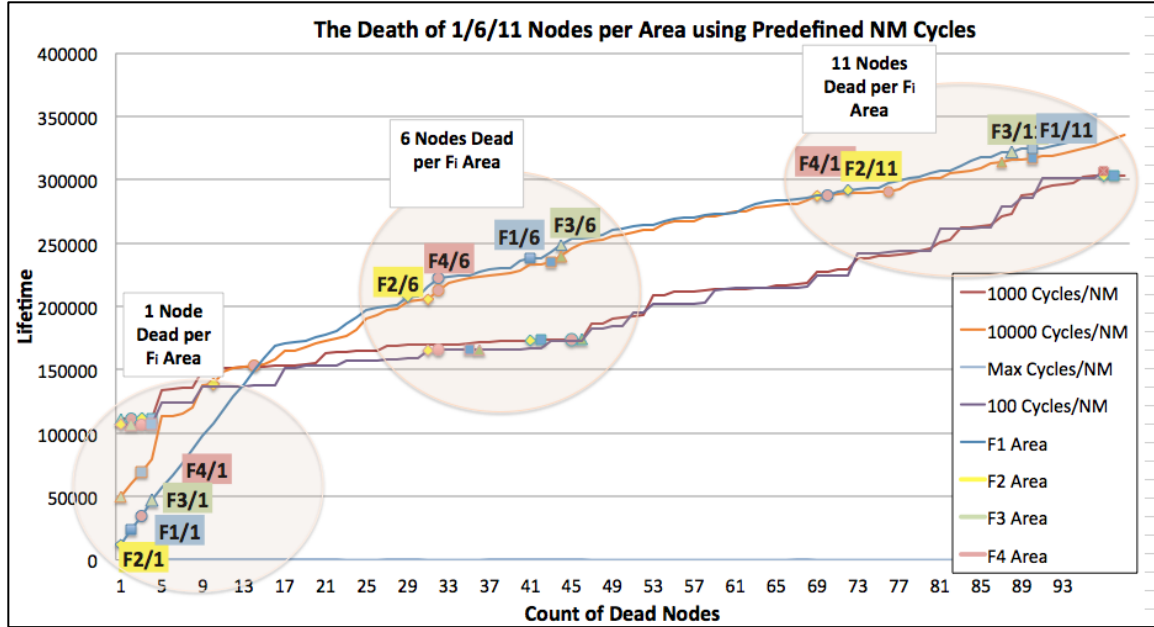
The choice of the cycle sets is based on the earlier simulations. The results of the previous section and herewith Figure 4-3 show that sensors that act as NMs for several cycles, these cycles range from 224 till 11683 cycles per NM, while the sensors that do not act as NM indicate a zero number of cycles. Hence, the lowest predefined number of cycles is chosen to be 100 cycles per NM to be close to the minimum of the cycles range and is increased by a factor of 10 and 100 cycles per NM. This results into the two other predefined sets, which are 1000 and 10000 cycles per NM, where the number 10000 is very close to the highest number of cycles that was reached in the prior simulations. With those three sets, most of the NM cycles range will be covered. Additionally, the figure shows in red the average number of cycles for the sensors that worked as NMs, which is equal to 6621 cycles per NM. It also demonstrates in green the overall cycles average over the whole network, which includes the NMs and the active nodes, which is equal to 3443 cycles. It can be observed that only half of the sensors were able to act as NMs and most of the time for a very high number of cycles, while the rest of the sensors did not have the adequate energy that could enable them to act as NMs as well.



**Figure 4-3** The count of Cycles per NM is shown in addition to the average Cycles per NM and the overall Cycles average.

Thus, the rationale behind this experiment compared to the previous scenario, is to examine letting all the sensors act as a NM for a low number of cycles, in order not to exploit their energies all at once. This will allow the sensors that used to act for a little number of cycles, to be able to act as active nodes for a longer period of time and if they have sufficient energy more than that, they could act as NMs for several rounds. Consequently, the rotation on NM will be more frequent and the energy dissipation of the network will be more evenly distributed around all the sensors.

The next illustration, Figure 4-4, shows the lifetime curves using the three predefined NM cycles. Additionally, the three death criteria are illustrated on each curve. Likewise the lifetime curve that was obtained in Figure 4-2 is demonstrated in the same figure, in order to be able to compare the three fixed NM cycles cases with the original scenario. The curve is labeled as Max Cycles/NM, while the other curves are labeled respectively according to the number of cycles they are presenting.



**Figure 4-4 Different lifetime curves that illustrate the different cycle number per NM**

When the maximum cycles per NM technique is used, it yields the highest lifetime in most of the lifetime definitions compared to the other three assumptions. The only point, at which the Max Cycles/NM curve is not at its best, is when using the original lifetime definition, which is the AND rule. As illustrated at the bottom left of Figure 4-4, all the fixed cycles per NM curves have achieved higher lifetime than the Max Cycles/NM curve. Moreover, the diagram also shows that the behavior of the maximum number of cycles and the 10000 Cycles/NM curves are very close to each other, while the 1000 Cycles/NM and the 100 Cycles/NM are very similar. The reason for this is that the 10000 Cycles/NM are closer to the Cycles/NM average that was obtained in Figure 4-3, whereas the 1000 and 100 Cycles per NM tend to be closer to the overall cycle average. According to the desired application, Figure 4-4 is very useful in obtaining the most fitting number of cycles per NM along with the most adequate lifetime definition that enables the network to achieve the highest lifetime possible. This could be achieved by doing the following:

- Identifying the relevant death criteria according to the application requirement.
- Choosing the most suitable Cycles/NM curve.

- In addition to the above, a specific dead area  $Fi_{Area}$  could be determined ahead as well.

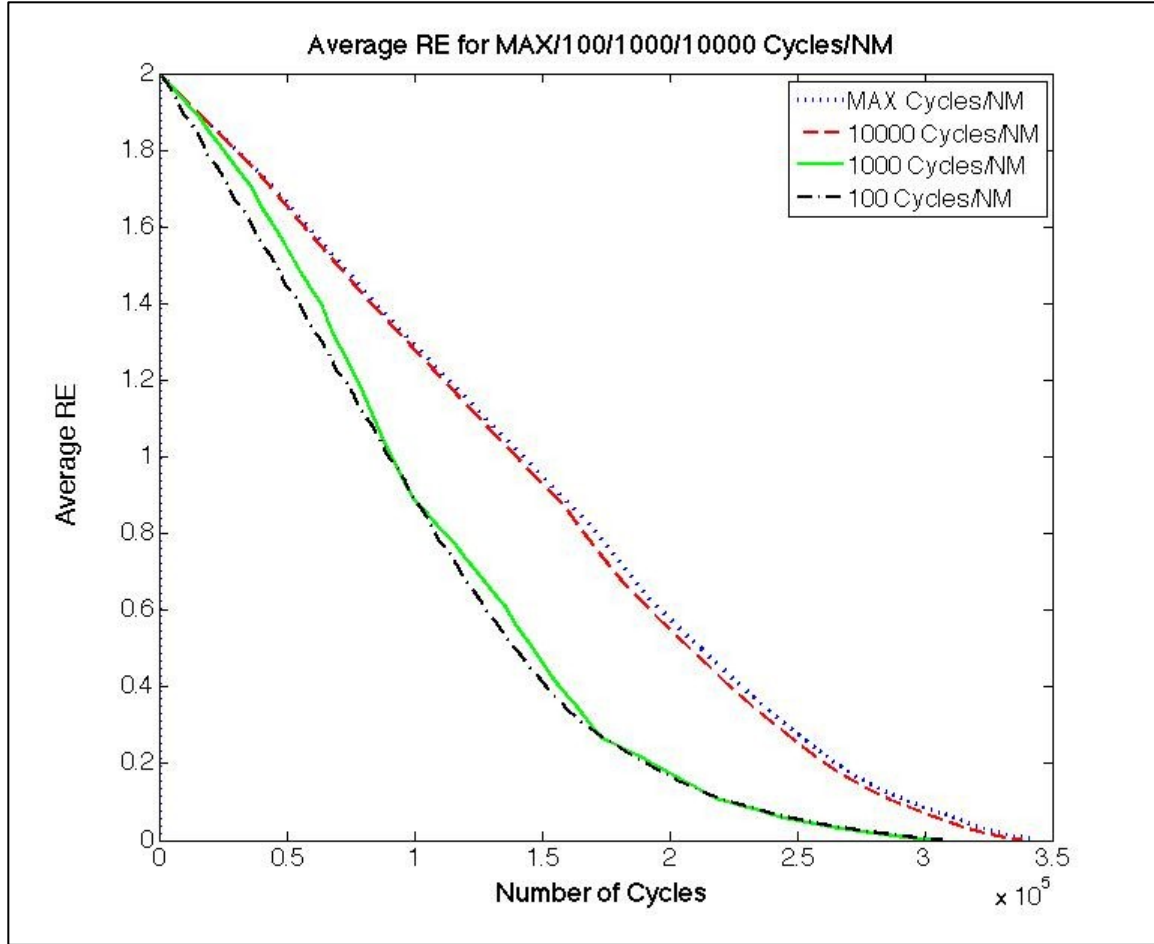
Nevertheless, there are still some factors that could not be obtained from this graph. One of them is whether the total energy within the network was consumed efficiently or not. In some applications, evenly distributed energy dissipation is required in order not to strain some sensors and leave the rest with high residual energy. There is always a tradeoff between achieving a high lifetime in the network, and depleting the sensors' energy efficiently. Hence, an additional diagram is needed in order to demonstrate the energy consumption in each of the previously described models, which will be shown in the following section.

#### **4.3.2 Energy Consumption Comparison of the Four Scenarios**

There are two similar methods that are able to visualize the energy consumption of each scenario. The first method is the calculation of the remaining energy of all the sensors at each cycle time, while the second scheme is calculating the standard deviation of the remaining energy of all sensors at each cycle time. Both methods will be explained next.

##### **A) The Average Remaining Energy Consumption**

Figure 4-5 illustrates the remaining energy consumption of the sensors at each of the different Cycles/NM approaches with respect to the number of cycles. The figure shows that the schemes with high number of cycles per NM like the Maximum and the 10000 Cycle/NM approach retain higher remaining energy in each cycle compared to the other approaches. This shows that setting a low number of Cycles/NM, like the 1000 and 100 Cycles/NM, will always yield efficient energy consumption. The reason for that is, when adopting a low number of Cycles/NM, the location of the NM changes more frequently. Thus, the cases where the NM is far from the sensor and is exploiting the sensor's energy not only due to its distant location but also due to acting as a NM for a long time, will be minimum, causing the sensor's energy not be exploited all at once.

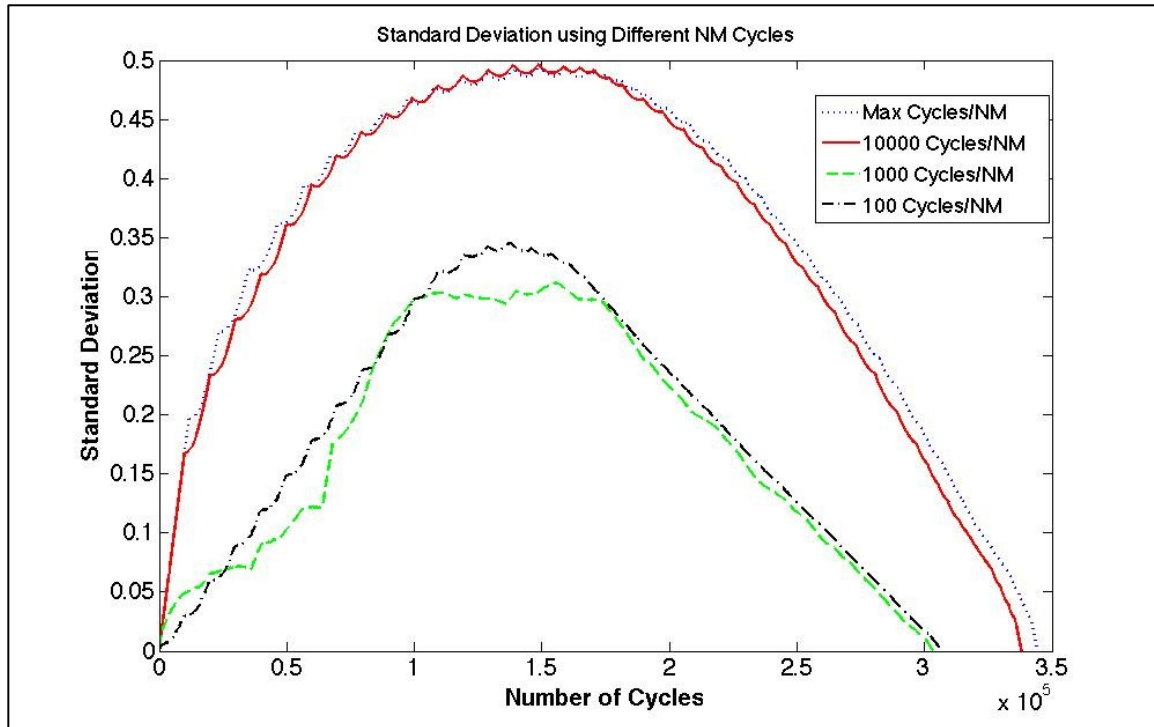


**Figure 4-5 Average remaining energy for the four scenarios using the ordered choice of NMs**

### **B) The Variance of the Remaining Energy Consumption**

The following figure, Figure 4-6, presents the standard deviation calculation of the remaining energy of the network sensors in every cycle. The illustration does not only emphasize what was displayed in Figure 4-5, but it also shows the distribution of all sensors' energy consumption during the whole network process. The curves in Figure 4-6 can be described as follows; at the beginning of the network cycle, all the sensors used to acquire the same energy level; that is why the standard deviation of the remaining energies of all sensors was at the zero level. By time, when part of the sensors starts to act as NMs and the rest as active nodes, the sensors started to lose a big part of their initial energy. Comparing all the curves at that point only, one can observe that, in the higher Cycles/NM, some sensors are losing their energies rapidly, compared to the sensors that

are using the low Cycles/NM. The reason for this is that, in the high Cycles/NM, some sensors are acting as NM for various cycles, causing the distant active nodes to lose their energies very fast, while the rest of the sensors within the network still possess high remaining energy. This difference in remaining energy between the sensors causes the value of the standard deviation to rise as seen by the Max Cycles/NM and 10000 Cycles/NM curve. A similar behavior happens to the other two curves 100 and 1000 Cycles/NM, but the value of the standard deviation at the middle of the graph is much lower due to not exploiting the far sensors from the NMs all at once, as explained in the previous section.



**Figure 4-6 Standard Deviation curve of the remaining energy using the ordered choice of NMs**

After the standard deviation reaches its peak, the curve starts to decrease again; this is where the sensors with high remaining energy start to lose their initial energies as well. When most of the sensors lose their energies and then their remaining energies start to cross the active node threshold, the standard deviation curve approaches the zero level, since most of the sensors will inhabit a similar remaining energy value. Furthermore, the

curves also show that using a lower number of Cycles/NM will result in a more even energy dissipation level, due to their lower standard deviation values, compared to the Max and 10000 Cycles/NM curves.

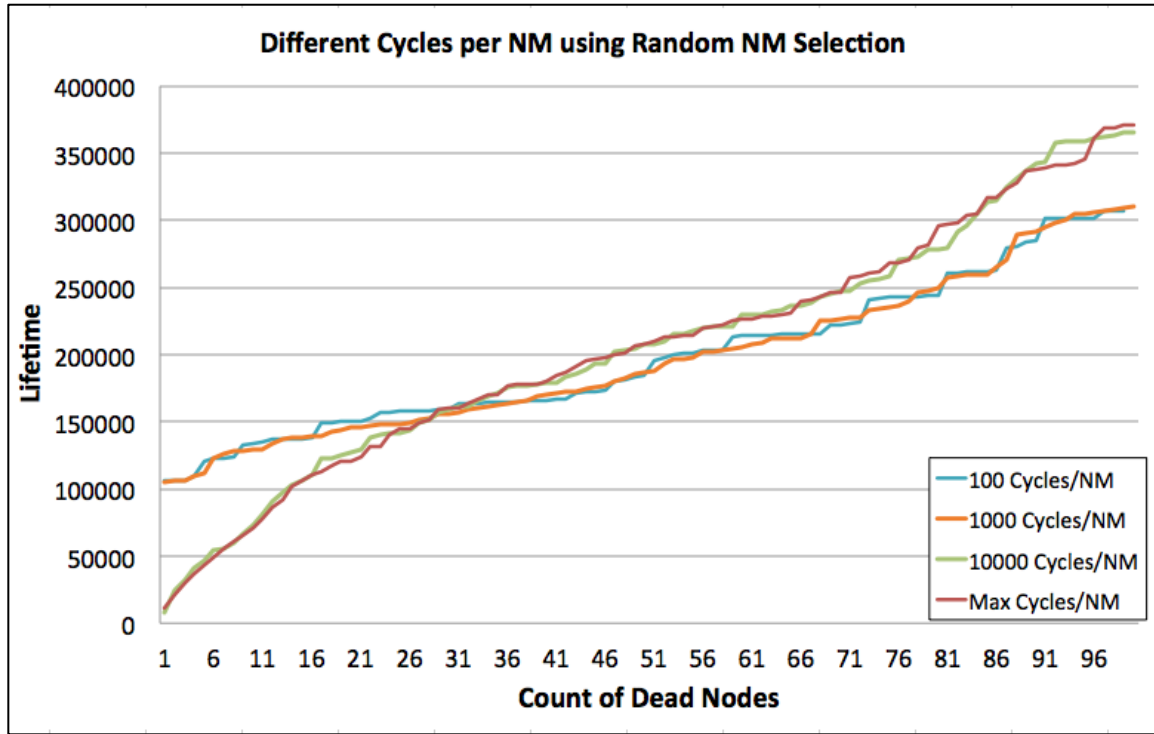
In all the previous simulations, the same NM selection process was used, which is choosing the NM in a circular path. This process will be investigated further in the next section in order to test its effect on the network and on the previous simulations.

#### 4.4 The NM Selection Approach

As mentioned before, the sensors in this wireless sensor network are uniformly distributed. Each sensor has an order number that differentiates its location from the rest of the sensors. The count of the sensors starts by the closest sensor to the sink and then goes in a circular path till it reaches the 100<sup>th</sup> sensor. Choosing the NM of each cycle also follows the same sensors' order; meaning the first sensor by the sink that should have sufficient energy at the beginning of the process, starts to act as an NM. When this sensor depletes most of its energy and reaches the NM threshold, it starts to act as an active node. Afterwards, the next node in line is checked whether its remaining energy is above the NM threshold or not. If this is true, then it will start acting as the next NM; if not, the following NM will be checked the same way. This process is called NM selection in a circular path. To verify if this process actually affects the results illustrated in the prior sections or not, a random process of selecting the NM will be examined.

The process starts by randomly selecting a sensor out of 100 to act as an NM for a specific number of cycles, depending on the chosen scheme. Then the next sensor inline will also be randomly chosen, out of the 99 sensors left, to act as a NM and so on. Figure 4-7 presents the different lifetime schemes together, each with a different number of Cycles/NM using the random NM selection. It shows that the lifetime curves have similar behavior compared to Figure 4-4 even when using the random NM selection. This means that that maximum and 10000 Cycles/NM techniques remain the highest curves with respect to the lifetime. Then the 1000 and the 100 Cycles/NM curves come next.

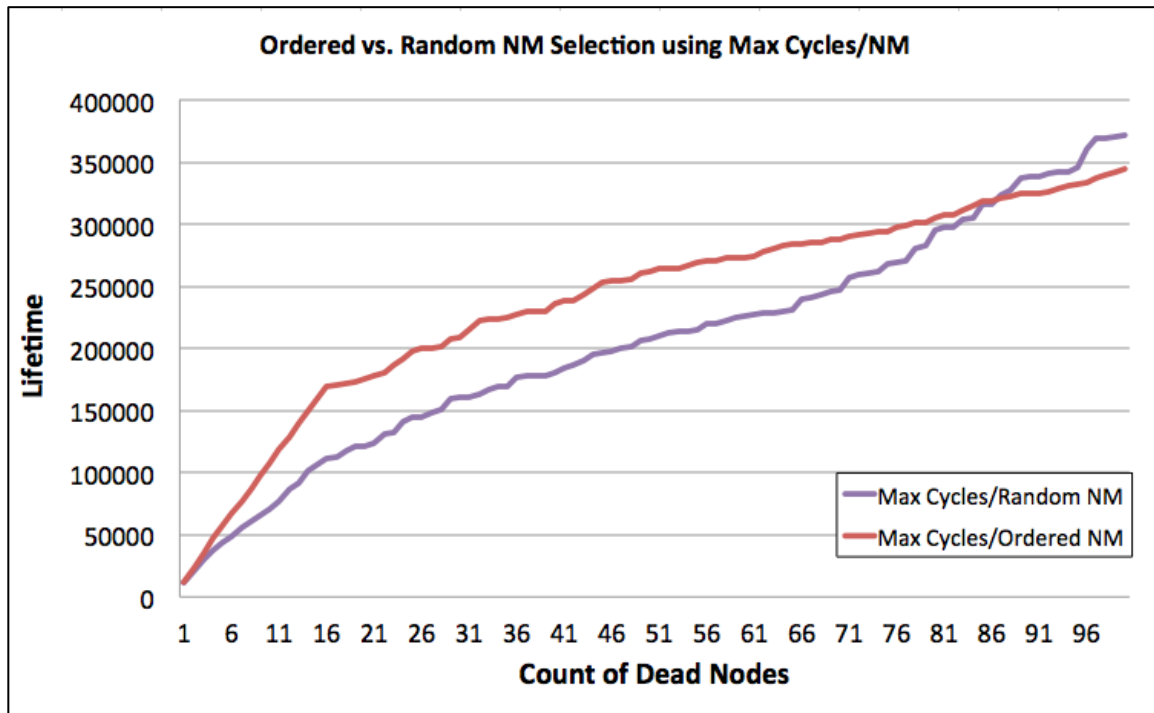
However, the four curves are closer to each other, meaning they are achieving lifetime values that are unlike the previous simulations.



**Figure 4-7 Different lifetime curves with different cycle count per NM using the random selection of the NM**

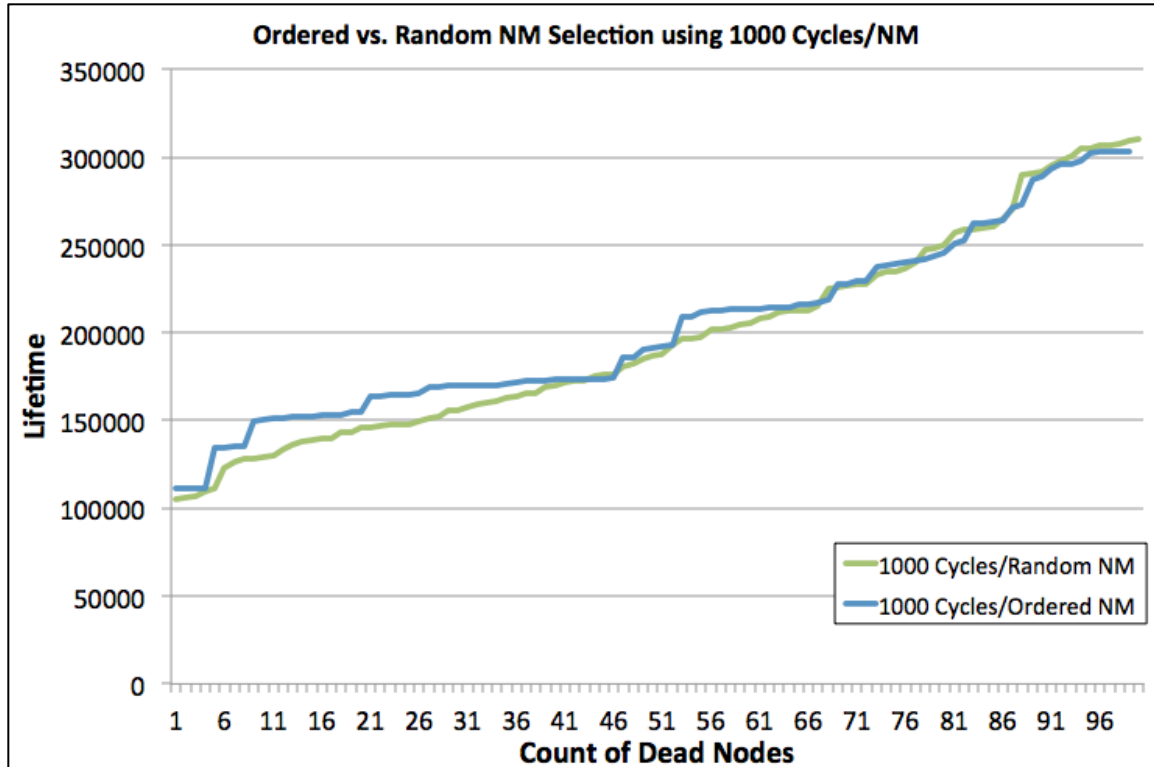
Hence, the only difference that the random NM selection has made is the shift in lifetime value. When comparing for example the maximum Cycles/NM curve using the ordered NM selection and on the other hand using the random NM selection, one can obtain a significant decrease in lifetime as shown in Figure 4-8. The random NM selection is achieving a lower lifetime value until the death of the 86<sup>th</sup> node; it then starts to attain higher lifetime compared to the ordered NM selection curve. The reason for that as mentioned before in the previous section is that when the selection of the current NM changes more frequently, it affects the network by not exploiting the far located sensors all at once. Instead, it averages the energy dissipation over the whole network, since the location of the NMs is changed more frequently. But at the same time, it causes the lifetime value to decrease compared to the NM curve.





**Figure 4-8 Comparing the Maximum Cycles/NM using the ordered NM selection and another time using the random NM selection**

For additional verification that the random NM selection has an effect on lifetime, another example is obtained in Figure 4-9, which compares the Ordered vs. the Random NM selection using a defined number of cycles, which is 1000 Cycles/NM. In this example the ordered selection of the NM is very similar to the random selection since in both cases NM location changes more frequently, when comparing that to the maximum technique. Nevertheless, there is still a slight difference in lifetime value between the ordered and the random NM selection. The ordered NM selection causes the Network to achieve higher lifetime during most of the network lifetime, while the random technique achieves higher lifetime only at the end of the network lifetime.

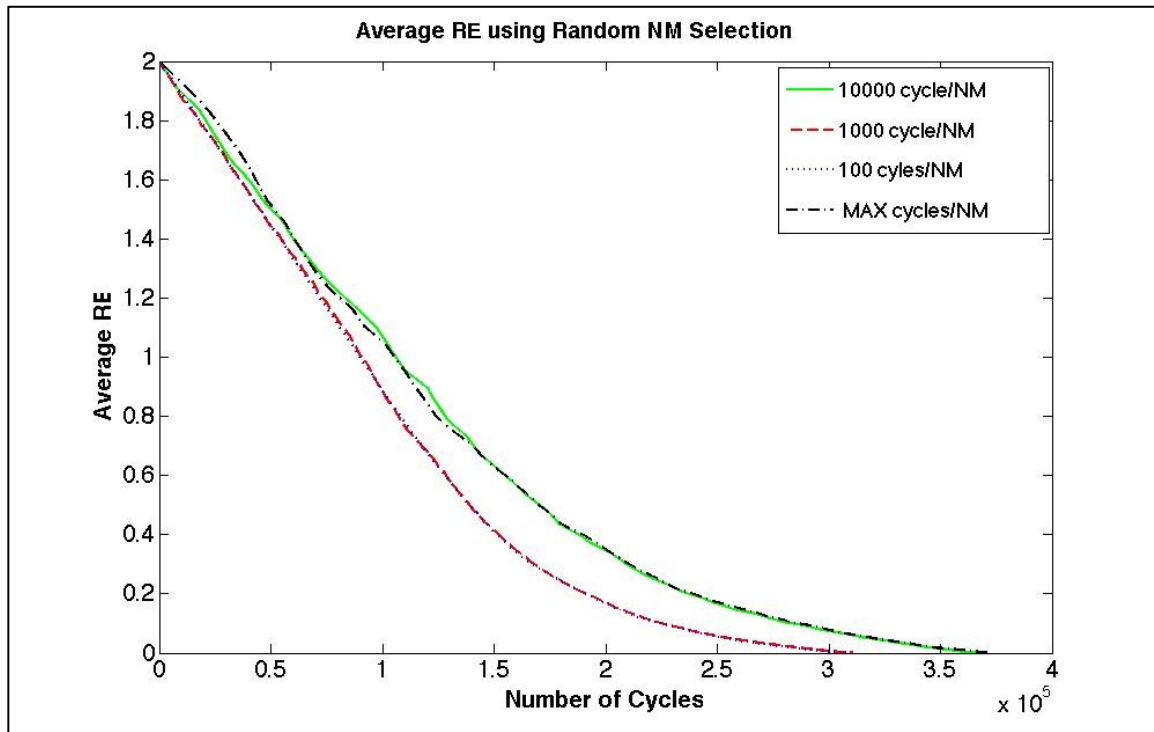


**Figure 4-9 Comparing Ordered vs. Random NM Selection using 1000 Cycles/NM**

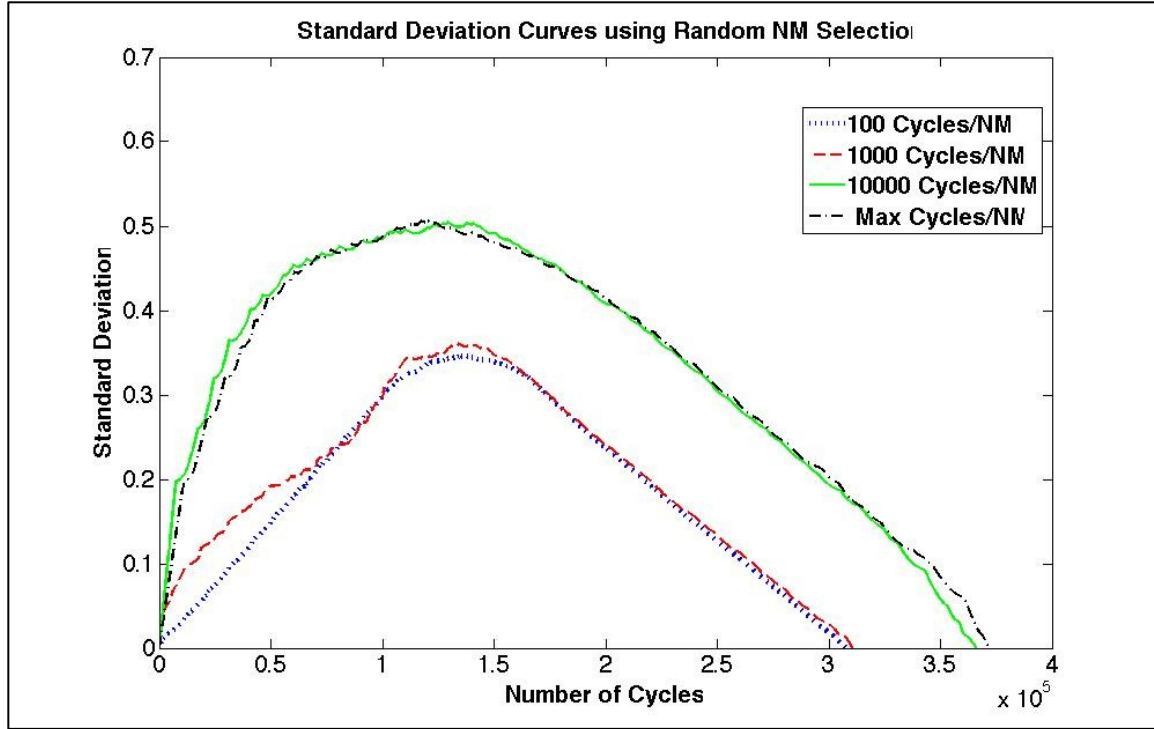
The same reason that was previously described under Figure 4-8 will be applied here as well. The random technique averages the energy dissipation over the whole network, reducing the remaining energy and exploiting the network's energy to the maximum. This could be deeply observed using the average remaining energy and the standard deviation curves, shown in Figure 4-10 and Figure 4-11.

Figure 4-10 shows the average remaining energy of all the curves using the random NM selection. Comparing this figure with Figure 4-5, one can observe that the maximum and the 10000 Cycles/NM curves are the ones affected the most by changing the NM selection procedure. However, the 1000 and the 100 Cycles/NM curves almost attain the same behavior. Figure 4-10 shows that the maximum and 10000 curves are skewed more closer to the 1000 and 100 curves, which means that the average remaining energy per cycle is much lower than the previous simulation in Figure 4-5. This proves that in this case the random NM selection has consumed the overall network's energy more efficiently as opposed to using the ordered NM.

For further validation, the standard deviation curves are also illustrated in Figure 4-11. One can also obtain the different behavior for the maximum and 10000 Cycles/NM techniques using the NM random selection. The top of the curves are skewed more to the left compared to Figure 4-6, which means that there are some sensors that have lost their energies a bit faster causing a high difference in the remaining energies of all the sensors. However, the sensors that possess high energy start losing their energies very slowly; this is why the curves go down very slowly and not abruptly like in Figure 4-6. They also reach the higher lifetime value when the standard deviation curves approach the zero level.



**Figure 4-10 Average remaining energy for the four scenarios using the random NM selection**



**Figure 4-11 Standard Deviation curve of the remaining energy for the four scenarios using the random NM selection**

The previous experiment shows that the NM selection procedure is independent of the choice of the number of Cycles/NM, as curves achieve the same behavior according to each other if the random or the ordered NM selection is used. However, if each single scheme is compared with itself using both procedures, a difference in lifetime value and in the energy consumption can be obtained. This simply shows the tradeoff between achieving a high lifetime value and exploiting the sensor's energy to the maximum. Therefore, depending on the application and also on the applications requirements the decision of selecting between both methods is made.

## 4.5 Chapter Conclusion

In Chapter 4, three different death criteria that depend on different measurement aggregation techniques have been assessed. These definitions are application dependent and therefore choosing between them is according to the application requirements. The first two criteria were the AND and the OR rule representing the known logical gates.

The third rule was the Majority rule. The effect of these definitions was examined on the network and the output graphs of this experiment can be used in selecting the adequate definition according to the desired application.

Furthermore, in this chapter, the effect of changing the number of sensing cycles per NM was examined. Fixed numbers were used for the NM/cycles count instead of exploiting the NM energy till the NM threshold is reached. Three different fixed NM cycles were introduced, which are the 10000, the 1000 and the 100 Cycles/NM. The analysis showed that using a predefined number of cycles per NM has caused the network to achieve a lower lifetime value in general, however the sensor's energy was consumed efficiently. Therefore, several graphs will also be used in order to be able to choose the suitable technique for the required application.

Finally, the choice of NM selection was investigated further in order to find whether it has an effect on the previous experiments or not. The selection of NM used to happen in an ordered circular path; however, in this experiment a random NM selection was introduced. The results show that the random NM selection does not have an effect on the behavior of the previous examples according to each other. Nevertheless, if in each single example the ordered and the random selection is compared on its own, a slight difference in lifetime and also in energy consumption could be found. This shows that, using the random NM selection, the network's energy can be consumed more efficiently and also a higher lifetime value can be achieved but only at the death of the final nodes in the network; whereas, on the other hand, in general a higher lifetime value when using the ordered NM selection can be achieved. Once again several graphs have been obtained in order to enable the choice between both techniques according to the desired aim, since there will always be a tradeoff between the network's energy consumption and the achieved lifetime value.

In conclusion, it is very essential when selecting a WSN network to decide on the objective of this network, which could be prolonging the network's lifetime or consuming the network's energy evenly. It is also very important to consider the environment in which this network will be placed and accordingly decide on the network conditions. Consequently, a choice could be made between the suitable death criteria, the

number of sensing Cycles/NM and the NM selection procedure using the graphs presented in Chapter 4 to achieve the best combination that best fits the desired WSN network.

# Chapter 5

## 5 Conclusion and Future Work

Wireless Sensor Networks are based on distributed autonomous devices that are used in monitoring and reporting in a variety of applications such as military, environmental, health, home, commercial applications and much more. The EM pollution monitoring is considered in many sources as one of the environmental monitoring applications that measure the radiation that could affect the human's health. For example in dense urban areas several base stations co-exist in order to be able to cover the users located in that area. However, the drawback is that sometimes signals coming from the various base stations overlap causing a much higher transmission exposure. These radiations are in some countries not legally monitored; therefore a generic algorithm was developed based on the event-by-event algorithm in order to monitor these radiations. Using this algorithm it was possible to turn the main parameters from fixed to random variables in order to examine their effect on lifetime. Several scenarios were simulated and their outcome showed that the violation duration has the most effect on the lifetime. It has caused an increase in lifetime for this specific network between 7.53% and 17.36%. Moreover, several random distributions were applied in order to evaluate their effect on network's lifetime. The results show that uniform distribution has the least effect on lifetime, then the Gaussian has and finally the exponential distribution with the most effect. It has prolonged the network's lifetime by a factor of 13.08%. These simulations illustrate the capability and flexibility of the algorithm of choosing between the different parameters and accordingly applying the different distributions depending on the desired application.

The second part of this research focuses on solving one of the WSN constraints. Since WSN rely on sensor nodes that are battery-operated, there is always an aim of prolonging the network lifetime as much as possible and consuming the network energy efficiently. Therefore, three different lifetime definitions have been assessed using the previously developed generalized framework, which are the AND, OR and the Majority rule. Outcomes of these lifetime definitions were illustrated in several graphs in order to

facilitate choosing between according to the required application. Moreover, calculations are applied to efficiently compute the network master threshold, so that each sensor acting as a network master exploits its energy to the maximum. Additionally, the number of sensing cycles per NM was investigated further by fixing the cycle number instead of making the NM consume its energy all at once. Three different examples were introduced, which are 10000, 1000 and 100 Cycles/NM. Results have shown that using fixed Cycles/NM causes the network to obtain a lower lifetime than operating the NM cycles all at once, however the energy consumption among all sensors was evenly distributed and consumed efficiently. Furthermore, the process of selecting the NM was examined in order to assure that this selection technique does not have an effect on the previous outcome. Random instead of predefined circular selection is applied and the results show that the organized NM selection does not affect the overall behavior of the previous results. However, if same examples are compared to each other, there will be slight different in lifetime value and energy consumption, where the random selection consumes the NM energy more efficiently. All the simulated experiments show that there will always be a tradeoff between achieving the highest lifetime during the network process and consuming the sensors energy evenly. Therefore, using the resulted graphs is always very important in selecting between the different criteria according to the needed application.

The next step that should be investigated in the research is applying the different death criteria on a varying size of the network instead of having a fixed  $100 \times 100 \text{m}^2$  area. The number of sensors will then be increased to cover that area. Additionally, the sensors will be randomly deployed and their transmitting energies will be examined further according to their location in order to have a more generic example that suits real life applications.



## Chapter 6

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## Chapter 7

### Publications out of this Thesis

- [Nouh, 2016] S. Nouh, N. Elgaml, N. Ali, A. Khattab, R. Daoud, H. Amer, “Generalized Electromagnetic Pollution Monitoring using WSN,” Wireless Sensor Network, 2016, Vol.08 (06), pp.85-92.
- [Nouh, 2017] S. Nouh, A. Khattab, S. Soliman, R. Daoud, H. Amer, “On the Impact of the Death Criterion on the WSN Lifetime,” accepted for publication for the 2017 IEEE International Conference on Electro Information Technology (EIT), pp. 1-6, Lincoln, Nebraska, USA, May 2017.